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PERIPHERAL NERVE INJURIES

BY THE NERVE INJURIES COMMITTEE
OF THE MEDICAL RESEARCH COUNCIL
(*Editor* H J SEDDON)



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and the work for which each was responsible is noted in the table of contents.

Grateful mention must also be made of others who undertook much of the day to-day work of the centres and, in some cases, carried out a number of the investigations mentioned in this Report, namely Catherine C. Burt, J Doupe, John St. C Elkington, L. Guttmann W B Highet, R. D Hotston, Mrs. Shirley Jackson, A S Kerr Anna McGowan, J R. Napier A R. Parkes, A J Slessor B M Unkauf.

PREFACE

AFTER the First World War the Medical Research Council's Committee upon Injuries of the Nervous System prepared a Report on Peripheral Nerve Injuries which was published in 1920 (Special Report Series No 54)

Early in the Second World War a Nerve Injuries Committee was again appointed by the Council to continue and extend the work done by its predecessor in 1914–18 It was fitting that Dr George Riddoch, who had been Secretary of the first Committee, should be appointed Chairman of the new Committee, and but for his untimely death he would have been editor of this Report Whatever success has been achieved in Britain during the past decade in the investigation and treatment of nerve injuries owes much to his foresight, energy and ability to inspire enthusiasm.

From the first it was recognized that both the effective treatment and the investigation of nerve injuries demanded stable hospital conditions and facilities for re-examining patients who had been discharged These requirements could most fully be met in the home country and five Nerve Injuries Centres were established by the Ministry of Health and the Department of Health for Scotland as part of the Emergency Medical Service. The English centres were at Botley's Park War Hospital Surrey the Winwick Emergency Hospital Warrington Lancashire, and the Wingfield Morris Orthopædic Hospital, Oxford, under the direction of the late Brigadier W Rowley Bristow Professor Sir Harry Platt and Professor H J Seddon respectively In Scotland, the centres were at the E.M.S Hospital Gogarburn near Edinburgh and at the E.M S Hospital Killearn, near Glasgow under the direction of Professor Sir James Learmonth and Professor C F W Illingworth respectively These centres admitted patients irrespective of status—sailors, soldiers, airmen, civilians and pensioners alike, though naval personnel were for the most part dealt with by the medical service of the Royal Navy Those working in these centres owed much to the colleagues who had undertaken the primary treatment of patients wounds and who in spite of great pressure of work, had found time to write excellent notes on the nature and treatment of wounds, and on the original extent of paralysis. Their help in this and other ways is gratefully acknowledged

Every facility was given to ensure complete continuity of supervision When a man or woman was asked to return to a centre for re-examination the Ministry of Pensions gave valuable aid in providing free travel warrants for pensioners and compensation for time lost from work. To the extent permitted by the exigencies of war patients who had returned to duty in the Services were sent back by their Commanding Officers for examination

The research studies arranged by the Nerve Injuries Committee were of two main types First, there were the general investigations into various aspects of nerve injury which were undertaken at all the centres the information was uniformly collected and recorded and was then submitted to a rigorous statistical analysis. The most elaborate of these analyses was that concerned with the results of nerve suture. Secondly there were certain special investigations —for example, vasomotor phenomena were studied at Edinburgh, and an investigation of the effects of galvanism on denervated muscle was carried out at Oxford Work of this latter kind was usually concluded within a year or two and most of it was published in medical journals before the war ended At one centre (Oxford) animal experiments were also used, not only to solve a number

of problems that vexed the clinician, but also to elucidate the finer processes of nerve injury and regeneration

At all the centres material removed at operation was submitted to histological examination. Indeed, over the whole research programme the closest collaboration was maintained between the laboratory workers and clinicians and the combined studies many of which are presented here, provided yet another example of the fruitful results which accrue from such co-operation

The standard of clinical documentation was high It was possible for a worker who was investigating a particular problem at one centre to make use of notes compiled at another The case records have been preserved and remain available for further analysis, for by no means all the information in them has been published either in this Report or elsewhere.

The 1920 Report contained an account of the clinical features of nerve injury of the phenomena of recovery and of the principles of operative treatment, electrotherapy and splinting. It contained few statistical data, for few were available. The conclusions reached by the distinguished body of clinicians and laboratory workers who formed the Committee were that secondary suture was the most reliable method of operative repair preceded where necessary by extensive mobilization to permit the closure of large gaps that nerve-grafting was not justifiable that the value of neurolysis was doubtful and that the nature of causalgia was still undetermined. So sound were the views put forward in the 1920 Report, and so clearly were they presented, that they were still applicable twenty years later and, in response to a wide demand the Report was reprinted in 1942.

The plan of the 1954 Report is different, for no attempt has been made to present a systematic account of the diagnosis and treatment of nerve injuries. The Report consists of a series of studies by those chiefly responsible for the day to-day work of the five Nerve Injuries Centres not all of whom were members of the Committee. It is concerned, therefore, only with those advances in the understanding of nerve injuries made by British workers during the war years The contributions have been edited by members of the Committee, on whose responsibility the Report is presented to the Council.

The conclusions reached cover many aspects of peripheral nerve injury Diagnosis has been rendered more precise by the study of disturbances of autonomic function, sweating and vasomotor control by the use of nerve blocking and of nerve and muscle biopsy by the demonstration that strength duration curves are the most convenient of the many means of examining the excitability of voluntary muscle, and by the introduction of electromyography as a clinical method of investigation Studies of vasomotor phenomena and of vascular injury accompanying damage to a nerve have clarified the nature of certain consequences of nerve injury Although the pathology of causalgia is still unsolved, a reasonable hypothesis of its causation has emerged, based largely upon the fact that sympathectomy is often successful in relieving the pain. Rates of regeneration have been worked out with some precision as have many factors which contribute to good functional recovery after nerve injury for example galvanic stimulation for maintaining the volume of paralysed muscle. Primary suture is no longer regarded as ideal even in aseptic wounds the best treatment for a severed nerve is now thought to be early secondary repair The results that may be expected after suture of individual nerves are based on yearly assessments, according to a uniform plan, of motor and sensory recovery over a period of at least three years and, in a number of cases, over a period of five

years The closure of large gaps after extensive mobilization of the damaged nerve proved unsatisfactory and this stimulated re-examination of the possibilities of repair by grafting. Homogenous nerve grafting proved unsuccessful but the results of autogenous grafting are encouraging

The reader of these essays will be impressed by the absence of references to prolonged sepsis as a feature of war wounds During and after the First World War infection was the bane of war surgery In the Second War sepsis was brought progressively more and more under control by improvements in the surgical treatment of wounds and by the introduction of effective chemotherapeutic drugs and antibiotics The repair of injured nerves thus came to be undertaken within weeks rather than months after the infliction of the injury Further as a result of the high quality of treatment in the field reconstructive surgery which included the repair of injured nerves could be carried out under increasingly favourable conditions and nerve damage due to sepsis was conspicuously absent

It is fitting that tribute should be paid to the helpfulness and co-operation shown by the patients who were treated at the Nerve Injuries Centres, for in the absence of these qualities it would have been impossible to collect the information upon which this Report is based

In conclusion both the Council and the members of the Committee wish to express their great indebtedness to Mr H J Seddon for his work in guiding the deliberations of the Committee, on which he succeeded the late Brigadier Riddoch as Chairman, and for the time care and labour he has devoted to this Report at every stage of its preparation

MEDICAL RESEARCH COUNCIL
38 Old Queen Street
London S W 1

16th July 1954

CONTENTS

I

II

CONTENTS

I

III

VI

PERIPHERAL NERVE INJURIES

By the Nerve Injuries Committee of the Medical Research Council

I

PART I METHODS OF INVESTIGATING NERVE INJURIES

by H J SEDDON

1 Documentation

WHEN the late Dr George Riddoch was appointed Chairman of the Nerve Injuries Committee in 1940 he immediately introduced a procedure for case taking that was to be followed very closely at all five Nerve Injuries Centres. It was realized that clinical records would form the basis of much of the research that was to be carried out and great efforts were made to achieve the high standard at which he aimed Riddoch s list of headings was so precise that few modifications proved necessary the only substantial addition was a list of headings for operation notes which was contributed by the Oxford Centre. As a guide to others who may embark on similar work the procedure for case taking is given in full

PROCEDURE FOR CASE TAKING

Name

Date of birth
Home address
Service no., etc., and address of Unit
Date of admission

Civilian occupation
Date of joining Armed Forces

History

Abstract of notes from other hospitals. Such notes are sometimes inadequate and must be supplemented by questioning the patient, and, if necessary by writing to the hospitals for further notes. All notes from elsewhere must be clearly identified and quotation marks used as required.

Particular attention must be directed to the following points

(1) Injury
- (*a*) Date.
- (*b*) Occupation, position, etc. when wound was incurred whether patient was or was not engaged in military duties at the time. Whether the nerve lesion followed the injury immediately or whether it developed after operative or other treatment.
- (*c*) Nature of wound and by what means it was inflicted.
- (*d*) Presence, degree and duration of sepsis.
- (*e*) Previous chemotherapy
- (*f*) If healed, date of healing.

(2) Pain Detailed description under following headings
- (*a*) Site and reference.
- (*b*) Degree and quality—slight, moderate, severe, shooting, burning, etc. Give description in patient's own words and then attempt to assess its severity especially if there is or has been loss of sleep
- (*c*) Time relationship—continuous, intermittent, length of intervals of freedom.
- (*d*) Exciting and exacerbating factors—movement, temperature, position of limb, physical and mental state.
- (*e*) Relieving factors—as above.
- (*f*) Psychic disturbance.
- (*g*) Progress (*most important of all*)
  - (i) Time of onset after injury
  - (ii) Whether increasing or decreasing in severity and whether such change has been sudden or gradual.
- (*h*) Associated factors—colour change in skin, swelling of limb

(3) Paraesthesia detailed description as for pain. Numbness should be used to describe a positive sensation. By 'numbness' most patients mean merely sensory loss.

(4) Paralysis
 (a) Extent of paralysis immediately after injury enquire carefully whether there has been any recovery and, if so, in what muscle groups and sensory zones.
 (b) Present complaint e.g. (1) in some sciatic lesions difficulty in walking is due to pain and not to motor loss (2) in a median lesion even with advanced recovery the hand is almost useless for fine movements.
 What use can patient make of the limb?
 (c) Previous physiotherapy and splinting.

Summary of History

Date of wound. Date of healing. Sepsis. Evidence of recovery

Examination

(1) Routine examination of essential systems.

(2) Wound Detailed description of entry and exit wounds and of operative incisions. All measurements in centimetres and given in relation to neighbouring bony points.
 (a) Description of soft tissue scar degree of fixation to muscle or bone description of underlying fracture if present—here include latest X-ray report.
 (b) Tenderness—local and referred pain.
 (c) Neuroma. Try to estimate size and degree of tenderness. State exact site.
 (d) If wound overlies a main blood vessel, determine degree of injury to vessel and *always* apply a stethoscope for there may be an aneurysm.
 (e) Estimate site of injury to nerve.

(3) Passive movements of all joints of affected limb In the shoulder region it is useful to chart active and passive movements side by side.

(4) Attitude e.g. wrist-drop appearance of shoulder in brachial plexus injury

(5) Gait in lower limb injuries.

(6) Motor function
 (a) Wasting. Refer generally to muscle groups, but in the hand always to individual muscles. Measure wasting. Standard levels are
 Thigh—20 cm. below anterior superior spine.
 Calf—maximum diameter
 Arm—10 cm. above medial epicondyle.
 Forearm—10 cm. below medial epicondyle.
 (b) Voluntary power
 0 = Complete paralysis.
 1 = Flicker of contraction.
 2 = Contraction only with gravity eliminated.
 3 = Contraction against gravity only
 4 = Contraction against gravity and some resistance.
 5 = Contraction against powerful resistance normal power
 (c) Muscle Consistence, tenderness.
 (d) Trick movements. Full description.
 (i) Rebound movement.
 (ii) Passive stretching of inactive tendons and muscles.
 (iii) Supplementary movements of certain muscles.
 (iv) Anomalous insertion of certain muscles.
 (v) Anomalous innervation of certain muscles.
 (e) Reflexes.
 (f) Reaction to electrical stimulation. Always mention condition of skin and presence or absence of oedema.

(7) Sensory function First ask the patient himself to map out the area of sensory loss.
 (a) *Touch Anaesthesia. Hypoaesthesia. Hyperaesthesia.*
 (b) Pain Analgesia. Hypoalgesia. Hyperalgesia.
 (c) Tinel's sign.
 (d) Proprioception.
 (i) Postural sense
 0 = Complete loss.
 1 = Appreciation of coarse movement.
 2 = Appreciation of fine movement but not direction.
 3 = Appreciation of direction of fine movement but response slower and less reliable than normal.
 4 = Normal.
 (ii) Vibration sense.

(iii) Deep pressure
(1) Recognition
(2) Pressure pain.
(3) Localization
(iv) Stereognosis and two-point discrimination in certain recovering cases e.g. median.
(8) So-called 'trophic' changes Hair skin, nails, subcutaneous tissue.
(9) Vascular Pulses above and below lesion (if relevant) Skin colour Skin temperature. Oscillometry
(10) Sweating test.

Conclusion

(1) Level of lesion.
(2) Type of lesion
(3) Brief summary of anomalies or unusual features.

Proposed Treatment

Progress Notes

To be written at monthly intervals at first, and to be continued whenever possible over a period of not less than three years

OPERATION NOTES

Date Operation Surgeon Assistant Anaesthetist Anaesthetic Occlusive Bandage or Bag Duration of Application

(1) Approach length and course of incision exact route need not be given in detail unless it departs from accepted procedure.
(2) Scar describe extent and vascularity
(3) Results of stimulation *before* dissection of lesion.
(*a*) Current and electrodes.
(*b*) Motor effects at various strengths of current.
(4) State of nerve
(*a*) Proximal dimensions, colour consistence.
(*b*) Lesion describe in detail from above downwards dimensions, colour consistence and appearance after cleaning the nerve anatomical relations, and distance from bony landmarks.
(*c*) Distal.
(5) Anatomical points unconnected with the lesion origin of branches, etc.
(6) Mobilization (if resection is to be carried out)
(*a*) Extension of incision
(*b*) Effect of freeing
(*c*) Effect of flexion of joints
(*d*) Effect of stripping branches
(*e*) Effect of transplantation
(*f*) Effect of division of branches
} In each case note additional length gained.
(7) Partial closure of incision position of limb for suturing. State of bed.
(8) Suture Amount of tissue excised. Extent of gap Appearance of cut surfaces. Details of suture.
(9) Local application of chemotherapeutic agents. Final closure.
(10) Plaster
(11) Anti-tetanus serum.
(12) Time taken.
(13) Observations and conclusions.

2 Clinical Manifestations of Nerve Injuries

A MOTOR FUNCTION

(i) *Method of Grading Muscle Power*

The Nerve Injuries Committee adopted a system of grading muscle power that has long proved satisfactory in the documentation of cases of poliomyelitis it has the merit of requiring no special apparatus and is sufficiently objective to permit comparisons between assessments of muscle power made by different observers

0 = Complete paralysis
1 = Flicker of contraction.
2 = Contraction only with gravity eliminated
3 = Contraction against gravity only
4 = Contraction against gravity and some resistance.
5 = Contraction against powerful resistance. Normal power

An illustrated booklet prepared by Sir James Learmonth for the Nerve Injuries Committee was published by the Medical Research Council (1942) as a guide to clinical examination and more particularly of motor function Standard charts were in use at most of the Centres which enabled changes in voluntary power to be recorded in tabular form (Fig. 1)

MUSCLE CHART — FOREARM AND HAND

NAME — WARD — CASE NO

EXAMINER											
DATE	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]		
SIDE											
TYPE OF OPERATION											
BRACHIORADIALIS		2	1½	4							
EXT. C. RAD. L.		2½	3	4	4	4	4½	4½	4½		
EXT. C. RAD. B.		2½	2½	4							
SUPINATOR				?							
EXT. DIG. COM.				2	3	3	3	3½	4½		
EXT. DIG. MIN.	0			0	0	0	1	2½	4		
EXT. C. ULN.				?1	1	1	3	3½	4		
ABD. POLL. LONG.		0	?0	0	1	2½	3	4	4		
EXT. POLL. LONG.				0	2	2	3½	3½	4		
EXT. POLL. BREV.				0	0	?1	1	?	4		
EXT. INDICIS				0	?	?1	2	?			
PRONATOR TERES		2	3	3½	4	4½	4½	4½	4½		
FLEX. C. RAD.	0	1	?1	3	3	4	4	4	4½		
PALM. LONG.		?1			?		3½		0		
FLEX. DIG. SUBL.	2	3	3	3	3½	4	4	4½	4½		
FLEX. POLL. LONG.	1	3	3	3	3	3½	4½	4	4		
FLEX. DIG. PROF. (LAT.)	1	1	1½	2	3	3	4	4	4		
PRONATOR QUAD.											
ABD. POLL. BREV.							?	3	3		
OPPONENS POLL.	0	0	0	0	0	0	1½	3½	4		
FLEX. POLL. BREV.							1½	?1	4		
LUMBRICALS 1, 2.							0	0	0		
FLEX. C. ULN.					?	2	3½	4	4		
FLEX. DIG. PROF. (MED.)							2½	2½	3		
ABD. DIG. MIN.											
OPP. DIG. MIN.							0	2½	3½		
FLEX. BR. DIG. MIN.											
DORSAL INTEROSSEI	0	0	0	0	0	0	[illegible]				
PALMAR INTEROSSEI							0	0	?1		
LUMBRICALS 3, 4.							1				
ADD. POLLICIS.											
ELECT. CONDUCTION											

5	N	Normal	Contraction against powerful resistance
4	G	Good	Contraction against gravity and some resistance
3	F	Fair	Contraction against gravity only
2	P	Poor	Movement only with gravity eliminated
1	T	Trace	Flicke of contraction
0	0	Zero	Compl t paralys

(V Voluntary power — M Muscl tenderness — S Pain on stretching
(C Contracture — F Faradic response — G = Galvanic response

FIG. 1 Chart showing recovery in the muscles of the forearm and hand after a gunshot wound of the brachial plexus. = voluntary power faradic response or

(ii) *Anomalous Innervation*

It soon became apparent that intelligent interpretation of the extent of paralysis was not possible without some knowledge of the commoner anomalies of innervation, in particular those of the muscles of the hand Interest in the subject had previously been confined to anatomists whose observations were frequently contradictory (Brooks, 1886 Spourgitis 1895 Riche, 1897 Poirier 1901 Frohse and Fränkel 1908 a good review by Hovelacque, 1927 Wood Jones 1941)

In 1943 Highet found that in 20 patients with division of the median nerve flexor pollicis brevis was paralysed in only four yet in 25 patients with division of the ulnar nerve only one showed any wasting of this muscle These facts strongly suggested that the muscle had a double innervation Murphey Kirklin and Finlayson (1946) published observations on a large number of cases treated in the United States, and in 1949 Rowntree reviewed the cases of division of the median and ulnar nerves admitted to the Oxford Centre. His findings are presented with such commendable brevity that they are given almost verbatim

There was no certain evidence of innervation of any thenar muscle by the musculo-cutaneous or the radial nerve the anomalies concerned only the median and ulnar

Tables 1 and 2 show the possible combinations of nerve supply It is seen that the text book description is the commonest arrangement abductor pollicis brevis, opponens pollicis and flexor pollicis brevis being supplied by the median and the others by the ulnar nerve. There is an inconsistency in the figures, however for flexor pollicis brevis remains active in most of the median (two thirds) as well as in most of the ulnar injuries (over half). This, of course, is because flexor pollicis brevis usually has a double supply and the loss of one component may not appreciably alter its power

Figs 2 to 4 show the common arrangements pictorially with emphasis on the innervation of flexor pollicis brevis. Fig. 2 shows the pattern in about a third of the ulnar lesions and in slightly more of the median lesions, and in one third of the whole. Fig. 3 shows that there was clinical evidence of dual innervation of flexor pollicis brevis in about one case in six. Fig. 4 represents the findings in about half of the ulnar lesions and in one in ten of the median lesions that is in one third of the whole These three groups made up four fifths of the total

It is significant that *one fifth of all the cases studied had an anomalous nerve supply of some kind* On referring back to Tables 1 and 2, it is seen that six cases had an unusual innervation of abductor pollicis brevis alone. In one of the six the muscle was supplied by the ulnar nerve (Table 2, last column) In the other five, all median injuries (Table 1 columns 1 and 9) it is not certain why abductor pollicis brevis remained active

Apart from these cases, there is every gradation from *complete ulnar* to *complete median* innervation of the intrinsic muscles of the hand Fig. 5 illustrates one extreme in which all the muscles were innervated by the ulnar nerve. This was found in four patients, all with median lesions to these may be added another three whose only motor loss was weakness of abductor pollicis brevis.

At the other end of the scale are the cases of median innervation of each of the four thumb muscles (Fig. 6) with median innervation of one or more interossei in addition (Fig. 7) There were five such cases (Table 3) with a sixth in which there was dual innervation of adductor pollicis and of several interossei (Case R)

Table 3 gives further details of these six cases. It will be seen that only two of the ulnar lesions were at the wrist, the other four being at the elbow Case D had an injury of the ulnar nerve at the elbow but no paralysis of the hand muscles A median block at the elbow produced complete paralysis of the hand muscles. Percutaneous stimulation of the ulnar nerve at the wrist, however produced strong contraction of all the interossei. This suggested that the motor supply to the interossei travelled as far as the elbow in the median nerve and then crossed over to the ulnar nerve in the forearm In Case H the converse obtained this patient had a low ulnar lesion, but electrical stimulation of the ulnar nerve at the elbow produced a good contraction in the hypothenar muscles, the first dorsal interosseous, the adductor pollicis and the palmar interossei these findings suggested an anastomosis between the ulnar and the median nerve in the forearm.

Conclusions

1 Voluntary activity of any given muscle in the hand is not an absolute indication of the integrity of the nerve which is usually held to supply it

2. Significant variations in the standard pattern of innervation have been found in one in five of 226 cases studied

3 The pattern of innervation described in standard text books occurred in only one case in three.

4 A striking variation is the supply of every thenar muscle by the ulnar nerve. In other cases the first dorsal interosseous muscle may be supplied by the median nerve.

5 In order to arrive at an accurate diagnosis when anomalous innervation is suspected, nerve blocks at appropriate levels are required (see p 8)

Another fairly common anomaly though its frequency has not been determined precisely is in the innervation of flexor profundus digitorum It is not infrequently found that the inner three quarters of this muscle activating the tendons to the middle, ring and little fingers, are supplied by the ulnar nerve, and in such a case it is usual to find that flexor pollicis brevis is also supplied by the ulnar The parts of the muscle connected with the third and fourth digits may receive a double innervation, and in a few cases the median innervation has extended to the part of the muscle moving the little finger In no case has the ulnar innervation been found to extend to that part of the muscle connected with the index finger

(iii) *Anomalous Muscle Action*

This term is used to describe unusual action of a muscle without reference to its nerve supply Two types are recognized—supplementary and trick movements.

The term 'trick movement should be interpreted as one of warning to the inexpert examiner for it is he who may be tricked These movements are all passive and result (Wood Jones, 1919) from

(1) tension on paralysed muscles by the strong action of their antagonists e.g. in radial paralysis strong action of the wrist flexors will cause the paralysed extensors of the fingers to extend the metacarpo-phalangeal joints

(2) rebound movements which occur when a normal muscle relaxes and the natural spring in the paralysed antagonists, e.g. the extensor of the toes, produces a small movement and

(3) movement produced by the action of gravity

Provided that the existence of such trick movements is recognized no difficulty should arise

TABLE 1

102 Median Nerve Lesions

Number of patients	4	3	13	14	38	16	10	1	1	1	1
Abductor brevis											
Opponens pollicis											
Flexor brevis											
Adductor pollicis											
	Fig. 5				Fig. 2	Fig. 3	Fig. 4				

Paralysed indicating median nerve supply
Weak, indicating dual nerve supply
Fully active, indicating ulnar nerve supply



TABLE 2

124 Ulnar Nerve Lesions

Percentage	29	15	52	1	4	1
Number of patients	34	19	64	1	5	1
Abductor brevis						
Opponens pollicis						
Flexor brevis						
Adductor pollicis						
	Fig. 2	Fig. 3	Fig. 4		Fig. 6	

Fully active indicating median nerve supply
Weak, indicating dual nerve supply
ralysed indicating ulnar nerve supply



TABLE 3

SIX ULNAR NERVE LESIONS

NAME	LEVEL	DORSAL INTEROSSEI				PALMAR INTEROSSEI			HYPO THENAR
		1	2	3	4	1	2	3	
Da J	ELBOW	■			■	?	?	?	
D	ELBOW	■	■	■	■	■	■	■	■
H	WRIST				■	?	?	?	■
J	WRIST	■	■	■	■	■	■	■	■
R	ELBOW							■	■
T	ELBOW	■	■	■	■	■	■	■	■

Fully active, indicating median nerve supply
Weak indicating dual nerve supply
Paralysed indicating ulnar nerve supply



Table 3 This table gives further details of six cases in which the median supply exceeded that seen in the common patterns of Figures 2 3 and 4 Five of the cases had the patterns shown in Figures 6 and 7 while the sixth, Case R., had dual innervation of adductor pollicis.

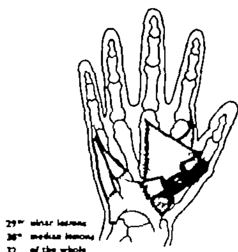


FIG 2. The pattern of innervation of the muscles of the hand in 32 per cent of cases flexor pollicis brevis supplied by the ulnar nerve see column 5 Table 1 and column 1 Table 2.

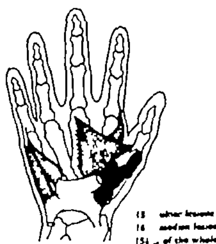


FIG. 3 The pattern of innervation in 15 5 per cent of cases. Flexor pollicis brevis supplied by both median and ulnar nerves see column 6, Table 1 and column 2, Table 2.

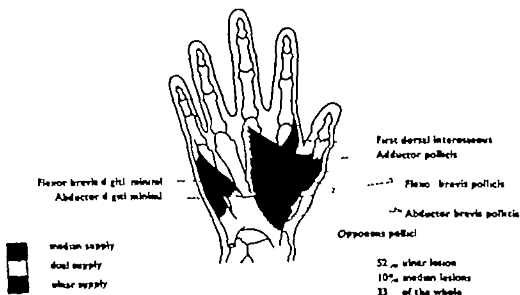


Fig 4 The pattern of innervation in 33 per cent of cases. Flexor pollicis brevis supplied by the median nerve see column 7 Table 1 and column 3 Table 3 This is the pattern of innervation described in anatomical textbooks.

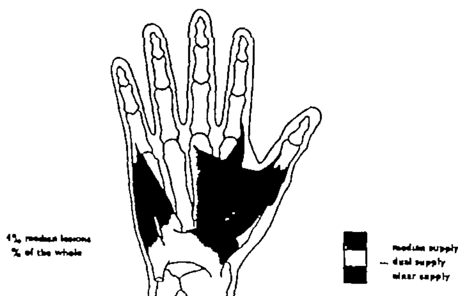


Fig 5 The pattern of innervation in 2 per cent of cases. All thenar muscles supplied by the ulnar nerve see column 1 Table 1

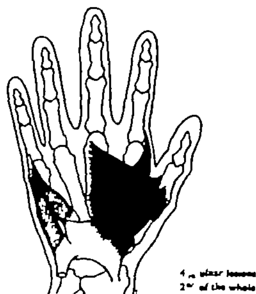


FIG 6. The pattern of innervation in 2 per cent of cases. All thenar muscles, including the adductor supplied by the median nerve see column 5 Table 2.

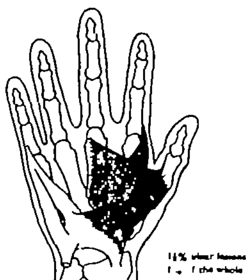


FIG 7 The pattern of innervation in 1 per cent of cases. All thenar muscles including the adductor and the first dorsal interosseous supplied by the median nerve see column 1 Table 3 cases de J and D.

upplementary movements are much more important and are performed uscles which are able to take over the function of a neighbouring one that ralysed The following are well known examples

(1) Active extension of the terminal phalanx of the thumb is not infrequently seen in complete radial paralysis and is produced by the action of abductor pollicis brevis in such cases a slip from this muscle is inserted into the radial side of the tendon of extensor pollicis longus

(2) Abductor pollicis longus acts as a flexor of the wrist when the long muscles supplied by the ulnar and median nerves are paralysed

(3) At the elbow the common flexor group is sometimes able to flex the elbow when the biceps brachialis and brachioradialis are paralysed

(4) A powerful movement approaching full abduction of the shoulder may occasionally be possible in the presence of complete paralysis of the deltoid, and Highet (1942a) showed that the muscle responsible was supra spinatus.

B SENSORY FUNCTION

lethods of Examination

mple methods were used for the examination of all forms of sensibility

) *Touch* Cotton wool is a difficult material to use for testing cutaneous le sensibility since even a skilled observer cannot count on applying a pledget with constant pressure For this reason von Frey hairs were used of the type rated in Fig. 8 Nylon filaments were mounted in the head of the applicator



FIG. 8 Holder for von Frey hair made from the distal end of a bicycle spoke. The handle is about seven inches long and the hairs are of nylon thread. This useful device was invented by Dr Graham Weddell.

calibrated by pressing them against one pan of a balance, the other pan g loaded with a known weight. A hair that just bends against a weight of is best for general use.

) *Pain* Spring algesiometers were attractive in theory but did not become ular in practice and all observers finally used a sharp surgical needle for ng cutaneous pain sensibility though the objection to cotton wool applies even greater force to a needle However a blunt spring algesiometer was d in one centre for determination of deep pressure and deep pain sensibilities

(c) *Postural sensibility* The standard practice was to hold the proximal and distal segments of the part to be examined by their lateral surfaces and then to flex or extend the joint through a range of movement that the patient could accurately appreciate on his normal side. The results were recorded in conformity with the grading described in the procedure for case-taking (p 1)

(d) *Thermal sensibility* Tests for heat and cold sensibility were not regularly employed since they did not provide any additional information of clinical significance.

(ii) *Anomalous Innervation*

Very considerable variations have been observed in the configuration of zones of cutaneous sensory supply but no systematic account of them has been prepared. It was noted that the autonomous zone of the median nerve in the hand may be very small indeed the ring finger may be excluded and loss of pain sensibility on the palmar surface may affect only the tips of the three lateral digits. Likewise the autonomous zone of the ulnar nerve may be limited to the little finger and the corresponding strip of the medial border of the hand. The autonomous zone of the superficial radial nerve may be completely absent Seddon (1947a) found sensibility preserved in eight out of 65 cases of proved division of the nerve. The area of cutaneous supply of the 5th and 6th cervical roots may vary from a patch on the lateral side of the arm to a long ribbon-like area extending distally as far as the thumb

(iii) *Tinel's Sign*

Most workers at the British Centres were more concerned with the unreliability of Tinel s sign than with its possible usefulness, but fortunately it was studied more constructively by Nathan and Rennie (1946) Henderson (1948) and Napier (1949) Henderson s experience was the most informative as a prisoner-of war he was able to make repeated observations on Tinel's sign in 400 cases of nerve injury and, being debarred for a time from operating on many of his patients whose damaged nerves were clearly in need of exploration he was in a unique position to assess the prognostic significance of his findings.

In his experience Tinel s sign became of consequence four months after the time of injury If strongly positive at the level of injury but persistently absent distally spontaneous regeneration could not be expected. If the sign was strongly positive at the level of the lesion and also appeared weakly distally poor regeneration would follow A strongly positive sign at the level of the lesion which gradually diminished as sensitivity of the distal part of the nerve increased progressed peripherally and faded centrally was a certain indication that satisfactory spontaneous regeneration was in progress Poor recovery attributed to great axonal confusion at the site of injury was observed in cases where the site of the lesion remained sensitive and a positive sign developed in the most proximal muscles within the distribution of the damaged nerve.

C NERVE BLOCKING

Although the technique of nerve blocking had previously been used in the investigation of other conditions, Highet (1942a) was the first to employ it with a local anaesthetic in the diagnosis of peripheral nerve injuries. He found it best to use a 2 per cent solution of procaine containing adrenalin at a strength of 1 in 50 000 In nerves that can be localized by palpation such as the ulnar at the elbow the radial in the mid arm or the lateral popliteal at the neck of the

fibula there is no difficulty in making the injection Cutaneous nerves can be localized and their course mapped out by percutaneous unipolar faradic stimulation But in the case of a deeply placed nerve the only guide is the standard surface marking. In all cases Highet used the apparatus shown in Fig. 9 which is designed to apply a unipolar faradic stimulus to the nerve to be injected it is indispensable for accurate work The outside of the injecting needle is coated with phenyl resin which insulates all but 1 or 2 mm at the tip The needle is attached to a standard syringe and the whole of this part of the apparatus together with the lead directly connected with it, is sterile. With this apparatus it is possible to apply a current direct to the nerve to be injected but only a very weak stimulus must be used The needle electrode is useful not only for precise localization of the nerve but for determining whether

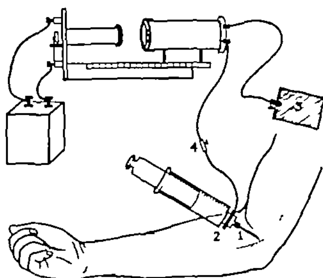


FIG 9 1 Hypodermic needle coated with insulating phenyl resin except at tip 2. Clip attached to metallic base of needle. The needle, syringe, clip and attached lead are sterile. 3 Indifferent electrode usually applied to thigh. 4 Connection between sterile and unsterile leads.

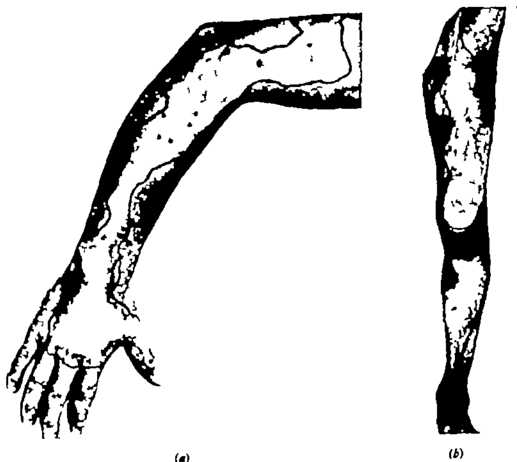
the subsequent block is complete Economy in the volume of local anaesthetic used is important since a large quantity may diffuse widely and anaesthetize neighbouring nerves. With the main trunks the aim is to inject the anaesthetic intraneurally but this is not possible with small nerves. By means of this method of nerve blocking Highet contributed much useful information on the anomalous innervation of muscles, on supplementary movements (notably of the supra spinatus and abductor pollicis brevis) and on variations in the cutaneous distribution of nerves Nerve blocking also proved valuable in determining whether a nerve lesion was complete or not, though it was not always possible to distinguish between partial damage and early recovery He was also able to demonstrate that the early shrinkage of zones of sensory loss was due to expansion of neighbouring zones which were normally innervated a phenomenon first described by Pollock in 1920

D AUTONOMIC FUNCTION

(i) *Sweating*

Guttmann's (1940) test with quinizarin was a great advance on older methods of demonstrating sudomotor activity and was often valuable as a guide to the extent of cutaneous sensory loss (Fig. 10 a, b) An objection to the method, however is that patients suffer considerable discomfort from being incarcerated for some time in a hot chamber Unless great care is exercised it is messy too since not only the patient and the heating chamber but also the room in which the tests are carried out inevitably become more or less contaminated with the powdered purple quinizarin dye. Nevertheless there is no more dramatic or accurate method of demonstrating the extent of loss of sweating.

Another test of sudomotor activity popularized by Richter and Katz (1943), is based on the increase of skin resistance when sweating is absent or greatly diminished A simple electrical circuit containing a galvanometer and an exploring electrode is used, the changes in resistance being observed while the electrode is moved across the skin The test is less delicate than Guttmann's for



(a) (b)

Fig 10. These photographs show the value of Guttmann's sweat test as a guide to the zone of sensory loss after nerve injuries of unusual character In (a) there was involvement of the whole of the cutaneous distribution of the radial nerve In (b) there was a complete lesion of the femoral nerve. In both cases the continuous lines mark the zones of anaesthesia, the dots the zones of superficial analgesia and the crosses the zones of deep analgesia.

it cannot show the pin point sweating that may be an indication of an incomplete lesion or of incipient recovery However this method of examination causes the patient no discomfort and is particularly valuable in small children as an alternative to sensory examination It may be used in the presence of an open wound where the quinizarin dye test is particularly undesirable

(ii) *Vasomotor and Nutritional Disturbances*

Richards has studied these consequences of nerve injury in detail and his observations are presented in full in the third section of this chapter

3 Classification of Nerve Injuries

During the First World War the consequences of division of a nerve became generally recognized but neurologists and surgeons fully occupied in dealing with the enormous number of cases requiring operative repair were not able to give as much consideration to the investigation of those in which something less than complete division was present, and in which a greater or lesser degree of recovery often occurred spontaneously Terms such as *contusion compression physiological interruption* and *injury of nerve-fibres with intact nerve-sheath* (Medical Research Council, 1920) were manifestly unsatisfactory and when employed, had vague or variable meanings.

During the earlier part of the Second World War Seddon (1942 1943) proposed a simple classification which he claimed was reasonably accurate from the histological standpoint and was of value clinically This classification has had a mixed reception some clinicians and more particularly experimental workers have welcomed it others have not though their objections have been based less on disagreement with the conception of the three types of nerve injury described than on aversion from the names used to describe them.

Neurotmesis (τμῆσις a cutting, which implies a separation of related parts) is the term used to describe the state of a nerve that has either been completely divided or is so seriously interrupted by scar tissue that, without surgical repair regeneration is altogether impossible. The term is more inclusive than *division* since it embraces lesions in which the nerve preserves an appearance of continuity but is, in fact, completely interrupted by scar formation such lesions are occasionally caused by gunshot wounds, frequently by traction injuries, sometimes by injections of noxious drugs such as the sulphonamides, and by ischaemia as in Volkmann s contracture.

Axonotmesis Here the essential lesion is damage to the nerve-fibres sufficiently severe to cause complete peripheral degeneration yet the stroma of the nerve remains in continuity More particularly the endoneurial tubes are intact regeneration occurs spontaneously and is of excellent quality since the endoneurial tubes guide the out-going streams of axoplasm back to their proper peripheral connexions (p 96) The lesion can be produced experimentally but it is not to be expected that the accidents of warfare or of civil life will produce lesions as uniform as those seen in the laboratory Nevertheless, as judged by their clinical behaviour fractures involving peripheral nerves cause axonotmesis with notable regularity (see p 82)

Clinically the most important point is that there is no immediate means of distinguishing between neurotomesis and axonotmesis in both there is complete degeneration of the nerve below the lesion and in both the picture is that of complete interruption From this it follows that other evidence must be taken into account in making a decision for or against exploration of the nerve

Neurapraxia (ἀπραξία, non action) the third type of injury is a benign disturbance of comparatively short duration The paralysis is predominantly motor there is little muscle wasting and no significant change in electrical excitability Subjective sensory disorders, such as tingling, numbness, and burning are common objective evidence of cutaneous sensory loss is always less pronounced than the motor disturbance and may be absent there is often a loss of postural and vibration sense and it is unusual to find any evidence of autonomic disturbance such as vasomotor sudomotor or pilomotor paralysis. It has been shown (p 95) that the lesion is predominantly one of the myelin sheaths, which explains why the motor and proprioceptive fibres, the largest and most generously myelinated of peripheral nerve fibres, are chiefly affected The axons remain in continuity and therefore it is not surprising to find that recovery usually occurs within a few days or at most, several weeks

The weakness of this classification not at first appreciated by its author is that it describes only what might be called three pure colours widely separated in a spectrum containing many intermediate shades. There can be no dispute about the state of a nerve that has been completely divided or contains a segment that has been converted into impenetrable scar tissue it is accurately described by the term neurotmesis. At the other end of the spectrum is pure neurapraxia, a condition that can often be diagnosed clinically with some confidence, though for complete certainty one must await the evidence provided by the speed mode of progression, and ultimate quality of recovery Likewise there are undoubted clinical cases of axonotmesis, and an experimental lesion of this type can be produced with ease (p 96).

But the violence that injures human nerves is completely haphazard in its effects the consequences can be predicted with absolute certainty only if it is clear that the injury has been such as to sever the nerve or to bring about total destruction of its essential elements. Although it is now possible to make a shrewd forecast of the consequences of a few types of injury—for example, a closed fracture is likely to produce axonotmesis a tourniquet neurapraxia—all violence that may be called sub-maximal is prone to cause mixed lesions, and this is especially so in the case of penetrating wounds. One funiculus of a nerve may be completely blocked by scar tissue and its state would be described by the term neurotmesis in a neighbouring funiculus only some of the axons may be interrupted while others are not only severed but disorganized by intraneural scar—a mixture of axonotmesis and neurotmesis while in yet a third the lesion may be a pure axonotmesis. In such a case it is beyond the wit of the most discerning clinician to describe the state of the nerve since nothing short of the most painstaking histological examination of the lesion could reveal what has happened However in the next chapter Zachary and Roaf show that in a fair number of cases it is possible to use the three terms in combination and in a manner that is clinically informative to that extent the usefulness of the classification may be considerably extended. Yet the fact remains that a collection of nerve fibres subserving many functions, differing in their vulnerability to injury and sometimes differently related in space to the line of injury is so complex a structure that no classification can possibly portray the consequences of every grade of violence.

The problem is indeed insoluble and we must rest content with a classification which, in a fair proportion of cases, gives an approximately correct picture of the probable extent of damage and of the kind of spontaneous recovery that may be expected.

4 Muscle and Nerve Biopsy*

Two useful ancillary diagnostic methods were introduced during the war and have since proved their worth in civil practice

A MUSCLE BIOPSY

Examination of biopsies has proved a fruitful means of following the changes in human voluntary muscle during denervation and re-innervation and there is still scope for further investigation (Bowden and Gutmann 1944 1945) The method has a limited but useful place in clinical work Recovery of motor function after peripheral nerve injuries, whether or not they are complicated by vascular lesions, is dependent upon adequate regeneration of the nerve and upon the condition of the muscles. It is therefore at times desirable to assess the state of the muscle as accurately as possible before embarking upon a prolonged course of treatment designed to restore voluntary movement which will be futile if the muscle is irreparably damaged In most cases when gross vascular damage is present the routine examination described by Holmes, Highet and Seddon (1944) will suffice and biopsy is not usually necessary It is of no immediate use to the clinician unless it can settle problems left unsolved by ordinary methods of investigation.

(i) *Method of Taking and Staining Biopsies*

A piece of the affected muscle is removed under local or general anaesthesia the size of the specimen varying with the type and size of the muscle. *The removal of a small portion of muscle is harmless provided it is not taken near the point of entry of the motor nerve where permanent damage might be inflicted on the nerve* If possible the piece should be at least 1·0 cm. long by 0·5 cm wide and thick it should be placed on a strip of cardboard to prevent distortion and fixed immediately in 10 per cent formol-saline. If the specimen is of sufficient size, half is used for frozen sections and the remainder is embedded in paraffin A modification of Bielschowsky's silver stain demonstrates the degree and pattern of innervation as well as the state of the muscle fibres Other sections should be stained with haematoxylin-eosin Van Gieson's stain and Sudan III or IV to define the intramuscular blood vessels connective tissue and fat If stained with phosphotungstic acid, paraffin sections give a more detailed picture of the muscle fibres than do frozen sections.

(ii) *Interpretation of Histological Findings*

A muscle biopsy is also usually a form of nerve biopsy for in all but 7 out of 140 specimens taken from 86 patients with nerve injuries, nerve fibres or empty Schwann tubes were found The characteristic changes in muscle fibres which are found during denervation and re innervation and in various types of vascular lesion are summarized in Chapter VII The state of innervation of the sample is also important. Signs of Wallerian degeneration the presence of empty nerve trunks and terminal branches are irrefutable evidence of a lower motor neurone lesion, whether due to a peripheral nerve injury anterior poliomyelitis or other anterior horn cell disease. The pattern of innervation and re-innervation gives some indication of the nature of the lesion in the main nerve trunk In evaluating the findings with respect to the pattern of innervation the level of the nerve

* This section on Muscle and Nerve Biopsy has been contributed by Ruth E. M Bowden

lesion in relation to the muscle and the time since injury have to be taken into account (see p 24) The finding of completely normal nerve trunks with grossly abnormal muscle fibres suggests a muscular dystrophy (Bowden and Gutmann 1946)

(iii) *Clinical Indications*

Where surgical repair of a nerve has been delayed beyond two years, it may be useful to take a muscle biopsy particularly if the sole purpose of the proposed operation is to restore voluntary movement. Where ischaemic damage is suspected from the history and from the consistence of the muscle, direct and histological examination of the muscle may prove valuable, for the presence of a normal pulse and normal oscillometric readings does not preclude the possibility of past ischaemia, particularly if the case is presented for treatment some time after the initial injury The combination of joint stiffness and oedema invalidates the usual forms of electrical testing, and if electromyography is either not available or the results are equivocal, a biopsy is essential befo embarking upon a long course of treatment or a series of operations.

In certain circumstances for example, the presence of gross scarrin diagnostic exploration of a main nerve trunk may be undesirable sometim even the results of exploration may be inconclusive and give little guide to tl procedure which should be adopted (see Case 2, Bowden and Gutmann 1945 In such conditions examination of a biopsy may be of assistance in diagnosin the type of lesion in the nerve, and in partial or recovering lesions may make possible to determine whether satisfactory regeneration of the nerve is takin place.

If there is any doubt about the essential nature of a paralysis, a biopsy serve to differentiate between one of myogenic origin, and a lower motor neuron paralysis.

Although the method has its uses its limitations must be recognized. It i open to error for unless the site of the biopsy is chosen with care or severa specimens are removed, a misleading impression is gained particularly if th lesion in the nerve is a partial one.

No neural elements were found in 5 per cent of a series of 140 biopsies however these specimens were not without some value, since the muscle fibre gave indirect evidence of the nature of the lesion of the nerve. Thus the appear ances characteristic of denervation indicate a degenerative lesion of the nerve while normal muscle fibres must be in functional connection with the lowe motor neurone If the biopsy is to be used to determine whether satisfactor re-innervation is taking place sufficient time must have elapsed for the regenera ting fibres to have reached the muscles.

B NERVE BIOPSY

In 1946 Holmes and Zachary pointed out that more immediate informatior about the state of the distal segment of a damaged nerve may be obtained by examination of a small piece of tissue taken from it. Since exposure of the nerve is necessary the method is clearly uncalled for if as is often the case, direct inspection of the lesion is sufficient to show the nature of the damage. However some lesions in continuity such as *those due to traction ischaemia* or the injection of noxious drugs such as the sulphonamides, present an equivocal

ppearance with perhaps little palpable thickening to disclose the severity of the ntraneural fibrosis In such cases sections of a funiculus removed from the erve just distal to the lesion will show whether regeneration is occurring. One nay also remove and examine a small piece from the site of damage.

i) *Methods of Taking and Staining Biopsies*

Two methods of obtaining samples have been employed The first is to acrifice a small sensory or motor branch and the second is to excise a funiculus rom the main trunk The first method is suitable only in certain regions, where n unimportant sensory or motor branch is available for example one of the ensory branches of the radial nerve in the musculo-spiral groove or one of he branches to flexor carpi ulnaris in an ulnar lesion above the elbow The alue of such a sample depends on how far it represents the state of affairs in he main trunk If there is a lateral neuroma and the resected branch arises on he same side as, and close to the lesion a fairly true picture of the extent of egeneration through the nerve is likely Where the biopsy is more distant, the ntraneural mixing of fibres between the funiculi will probably mean that a proportion of undamaged fibres will be present in the branch and the sample will therefore, be less reliable

When an unimportant branch is not available a funiculus from the main trunk may be taken Clearly when the lesion affects mainly one side of the nerve the same principle applies as in the case of the branch biopsy and the funiculus should be taken close to the most damaged part of the nerve and from the same sector of its circumference. The epineurium is incised longitudinally over a distance of about 2 cm. one funiculus is gently lifted up by blunt dissection and resected with a sharp knife or scissors Provided the site of biopsy is not close to the distribution of the nerve the removal of one funiculus is not likely to have any markedly adverse effect on the quality of recovery

The specimens are laid on small pieces of postcard they are attached to the card by pressure with forceps at both extremities, but should not be touched elsewhere The cards with the attached specimens are immediately placed in bottles of 10 per cent formol-saline in which they remain for two days or more. A reliable method of myelin staining, and also a silver technique for axon impregnation should be employed for each specimen. Some sections from each block are also stained by Masson s light green trichrome Transverse sections are best for the demonstration of myelin sheaths, and longitudinal ones for axons.

(ii) *Interpretation*

The interpretation of the biopsy presents some difficulties The recognition of normal nerve fibres and of those which have undergone complete Wallerian degeneration is as a rule simple but some uncertainty arises in attempting to assess the significance of the number and diameter of regenerating fibres when these are present The rate of advance of regenerating axon tips should be of the order of 2 5 or 3 mm a day but there is some delay of varying degree before the axons pass the level of injury and further development is influenced by many factors which affect the increase in diameter of the axons and the myelination of the regenerating fibres In spite of these difficulties in interpretation it is often possible to judge within fairly wide limits whether satisfactory re innervation is in progress.

PART II. RATES OF REGENERATION

by RUTH E M BOWDEN and D A. SHOLL

1 Introduction

SOME knowledge of the rate of recovery after various types of nerve injury is important to the surgeon, for it may influence the choice between operative and conservative treatment. For example, most radial palsies associated with closed fractures of the humerus recover spontaneously but in a few cases exploration is necessary since the nerve may be caught between the fragments or may be severed. If spontaneous recovery is taking place the first sign of voluntary contraction should be found within a certain period, and delay in recovery may be a strong indication for operative intervention Apart from these practical applications, measurements of rates of outgrowth of axon tips and of advance of recovery of function have been valuable, for they have shed light on some of the processes of nerve regeneration. Various estimates of these rates have been given by many workers, and these differences have been shown to be due, in part at least, to the techniques which have been employed for the different methods do not necessarily measure the same quantity

An analysis of the processes leading to functional recovery shows that the regenerating nerve fibres must pass through several phases (Young, 1942) After suture or a simple crush of a nerve trunk, the nerve fibres undergo some retrograde degeneration followed by branching and outgrowth across the scar The new axons advance down the distal stump to make connection with the end-organs. After this has been successfully accomplished the fibres must increase in diameter and acquire the appropriate degree of myelination, processes which themselves depend upon contact with the end-organs (Weiss, Edds and Cavanaugh, 1945 Aitken Sharman and Young, 1947) The density of such successful re-innervation must be adequate before function can return In addition some degree of reversal of atrophic changes in the end-organs themselves is necessary Thus, the problem of measuring rates of recovery of function is complex and the difficulties are increased by our ignorance of the rate of maturation of nerve fibres, the degree of maturation required for restoration of particular functions, and the rate of reversal of atrophic changes in the end organs. Experimental and clinical investigations were designed to estimate the various stages of the processes of recovery and it was soon seen that there is a distinction between the rate of advance of axon tips and the rate of advance of functional completion of the nerve fibres

2. Experimental Investigations

(i) *Rate of Advance of Axon Tips*

Young and Medawar (1940) compared the rate of regeneration of nerve fibres after fibrin and silk suture of the sciatic nerve in the rabbit. They used the pinch method of assessing the rate of regeneration At an appropriate time after suture the nerves were exposed mobilized and crushed with fine forceps at 1 mm. intervals, working from the periphery towards the suture. The first point at which a reflex response was obtained under light anaesthesia was found by histological examination (Bodian s method) to contain a few fine axons these were the more rapidly advancing fibres. This pinch method is more delicate than electrical stimulation because these immature nerve fibres have

a high threshold to electrical stimulation and a low one to mechanical stimulation (Konorski and Lubinska 1946)

Young and Medawar concluded that there was no significant difference between the rate of regeneration in the medial and lateral popliteal nerves The distance regenerated in mm was plotted against the time after suture measured in days These points were found to lie approximately on a straight line and regressions were calculated giving a mean rate of advance of axon tips of 3 88 mm per day after nerve suture The time at which the fibres entered the distal stump was calculated by extrapolation and it was found to be approximately nine days after the suture.

(ii) *Rate of Advance of Axon Tips and Rates of Recovery of Function*

A more elaborate experimental approach was planned by Gutmann Guttmann Medawar and Young (1942) for investigation of the rate of growth of nerve fibres and the rate of advance of the processes leading to functional completion of sensory and motor fibres in the sciatic nerve of the rabbit Care was taken to preserve the sural nerve and thus prevent trophic sores.

The 'pinch method was used to determine the rate of outgrowth of pain fibres in rabbits and in three dogs The rate of advance of functionally complete sensory fibres was measured by determining the time taken for return of sensibility to a given area of skin and by measuring the rate of shrinkage of the analgesic area. The animals were lightly anaesthetized and the skin was stimulated with a sharp needle, the return of functionally complete pain fibres being indicated by a flexor response (The results of the two latter types of experiment are given and discussed at length by Gutmann and Guttmann 1942a)

The rate of regeneration of functionally complete motor nerve fibres was estimated by determining the time at which reflex spreading of toes returned after injuries of the lateral popliteal nerve. This reflex is elicited by holding the animal by the scruff of the neck and lowering it suddenly The rate of motor recovery was also estimated by determining the times of recovery in muscles at varying distances from the lesion Injuries were produced at different levels in the nerves by crushing or by division and suture. It was therefore possible to analyse the effect of the nature and level of the lesion upon the rates of regeneration and functional recovery A few young animals were also investigated by similar methods to determine the influence of age upon regenerative processes The disadvantages of the methods were that the distances involved were small being limited by the size of the rabbit and it was possible to obtain only single readings from different individuals when the pinch technique was used or the time of return of sensibility to a given area of skin was measured The same objection applied to the determination of the time at which the toe spreading reflex returned (Gutmann, 1942)

Within the distance available the rate of advance of the axon tips did not depart significantly from linearity Later work has shown that over longer lengths this rate declines progressively (Sunderland 1948) Gutmann *et al* (1942) assumed a constant rate of regeneration and fitted straight regression lines to their data, which enabled them to calculate a so-called latent period by extrapolation. While such a regression line usually appeared to fit the data well in several instances the scatter and position of the points suggested that a curve might be more suitable, thus indicating a falling off in rate with time and distance which was particularly marked in the plots representing the rate of return of sensibility

In all tests of motor recovery no accurate allowance can yet be made for the *intramuscular course of the nerve fibres. In spite of these objections and the* limitations, which were recognized by the authors the experiments were of considerable importance There was abundant proof that regeneration and functional recovery were processes which spread along the nerve trunk and the rate of growth of the axon tips was shown to be higher than the rate of advance of restoration of functional capacity The scar delay or initial period, was *defined as the period which included the process of retrograde degeneration as* well as the penetration of the scar by the axon tips This period was calculated by extrapolation and was found to be nearly constant in all satisfactory sutures (7 3 days) after crushing at a single point the period was 5 2 days. When functional completion was studied a considerable increase was found in the delay before the apparent onset of the processes leading to recovery of function and *clearly retrograde degeneration and scar delay were not the only factors* involved. The total latent period before advance of recovery began was 36 days after suture and 20 days after crushing.

By using the pinch method, the rate of advance of the most rapidly growing axon tips was found to be 3 5 mm. per day after a suture and 4 4 mm. per day after crushing the lateral popliteal nerve. No significant difference was found in the rates of regeneration in the three divisions of the sciatic nerve, and there was no conclusive evidence that the level of the lesion affected the rate of regeneration of axons The rate of advance of functional recovery as measured by the return of the toe spreading and by return of a response to nociceptive stimuli to a given area of skin, gave rates of 2·0 mm. per day after sutures and 3·0 mm. per day after crushing. The shrinkage of the analgesic area of the foot proceeded less rapidly and was found to be 1 6 mm per day after suture and 2 1 mm. per day during recovery after crushing. These rates were significantly lower than those determined by the other techniques. It was suggested that there may be a decrease in the rate of regeneration in the terminal plexuses, and Weddell s work (see Chapter VII) shows that the distance between two points on the skin does not represent the whole of the distance through which the nerve fibres must travel The ramifications in the deep and superficial plexuses increase the distance by an unknown but probably significant, amount. *In rabbits of a month* old the rate of advance of the axon tips was found to be similar to that found in adults however the scar delay was less and maturation of the fibres proceeded more rapidly

Gutmann and Guttmann (1942a) found that the rate of recovery of sensibility was not only slower but more irregular after suture than after a simple crush. *When the nerve was crushed over a stretch* of 4 cm. there was a longer delay and a less satisfactory degree of recovery The level of the lesion influenced the rate at which the margin of analgesia receded. This rate was 2 3 mm. per day where the nerve was crushed at the ankle, and 1 8 mm. per day when the injury was in the thigh It was tentatively suggested that this decreased rate was due to the scattered arrival of new fibres after a high lesion.

3 Clinical Investigations

The experimental investigations are instructive, but the results cannot be transferred directly to clinical work. Apart from other specific differences, the distances involved in man are very much greater and the lesions in continuity are not comparable with a single crush produced in ideal experimental conditions.

(i) *Rate of Advance of Axon Tips*

Investigations of the rate of advance of axon tips are few and no statistical significance can be claimed for the results Seven patients who required amputation for a condition other than malignant disease or extensive infection consented to crushing or division and suture of the nerves of the parts to be sacrificed The amputations were then performed at suitable intervals after the preliminary experimental operation The nerves were examined for the presence of regenerating fibres In one case where an experimental axonotmesis had been produced an average rate of 4·4 mm per day was found in a digital nerve (Young, 1949)

From examination of the muscle biopsies there was evidence that the average rate of outgrowth of axon tips was not less than 3 mm per day after axonotmesis (Bowden and Gutmann, 1944) These few observations are in general agreement with the findings based on the study of Tinel s sign (1917) The rate of advance of Tinel's sign gives an indication of the rate of outgrowth of the axon tips and numerous observations are recorded by various workers amongst the first of whom was Dustin (1910 and 1917) Konorski and Lubinska (1946) made another experimental study of the problem. More recently Nathan and Rennie (1946) Sunderland (1946) Henderson (1948) and Napier (1949) have reported their observations. There is some evidence that the rate of advance of axon tips decreases with time and distance in man Napier studied 48 cases and found a mean rate of advance of 2·6 mm. per day and gives figures for axonotmesis and suture of the median, ulnar radial and sciatic nerves.

(ii) *Rates of Functional Recovery in Man*

Seddon Medawar and Smith (1943) investigated the rates of recovery in 25 cases of injury to peripheral nerves, 18 of these being radial nerve palsies. The process of recovery was followed by three methods observations of serial re innervation of muscles in a limb the advance of Tinel s sign and the rate of advance of returning sensibility The rate of recovery of sudomotor activity could not be measured for the process was found to be erratic.

The phases through which the regenerating fibres must pass before recovery occurs have already been discussed, but three important variables are encountered after suture of nerves in man, namely the delay before suture, the length of nerve resected and the effects of post-operative stretching. Three sets of data are required for study of the serial re-innervation of muscles the level of the lesion in relation to a convenient bony land mark, the points of entry of nerves into the muscles in relation to the same land marks, and the times of reappearance of voluntary contractions. The level of the lesion was measured accurately in those cases coming to operation and in others it could be judged fairly accurately by clinical examination The points of entry of motor nerves were studied by B Feinstein and W Bremner Highet who made a number of dissections. They found considerable variations in levels of entry of branches, even between two sides of the same subject, and there was no relation between levels of entry and the length of limb in subjects of different adult stature (The figures were published by Seddon *et al* 1943) No account could be taken of the intramuscular course of the nerves Patients were examined at intervals to determine the times of reappearance of voluntary contractions. This immediately introduced difficulties and a source of error for it was neither possible nor desirable to keep patients in hospital during the greater part of the period of recovery In some cases examinations were made at weekly intervals in others the interval ranged from two to four weeks When the progress of recovery had been

recorded the points were plotted on a graph showing the distances covered by the process of regeneration within certain periods of time. The initial period was calculated by extrapolation. In most cases a straight line fitted the data, thus suggesting that the rate of recovery was constant, but it failed to do so in others and curves had to be fitted, there being evidence that the rate of advance of the process of recovery decreased with time and distance. There were remarkable variations in rate and in the initial periods even for lesions of the same nerve in different individuals. However it was felt that the rates of recovery might be reasonably assumed to be constant over moderate ranges of time and distance. *In the early stages a rate of at least 3 mm a day was found* and this is comparable with the rate found in the rabbit. The following average rates of motor recovery were estimated in the radial nerve after suture 1·6 ± 0·2 mm. per day after lesions in continuity classed as axonotmesis 1 5 ± 1 mm. per day In all the nerves studied after suture the rates were 1 5 ± 0·2 mm. per day and after axonotmesis 1·4 ± 1 mm. per day The lower rates found after lesions classed as axonotmesis are unexpected however it is probable that some of these were not in fact cases of uncomplicated axonotmesis. In man, lesions in continuity are seldom comparable with a simple experimental crush, and may contain more scar tissue than a well-executed secondary suture. The average rate of advance of Tinel s sign after suture was found to be 1 7 mm. per day Other estimates of sensory and motor recovery were calculated from less complete data and from the data of Stopford (1920) but the authors considered that the observations were too few to merit discussion. A decreasing rate of recovery was demonstrated by Seddon *et al* (1943) in only a few of their cases, but the work of Sunderland and his colleagues and the observations of Napier (1949) on the rates of advance of Tinel s sign suggest that in man these rates decrease with time and distance in the majority of cases.

Since the investigation of Seddon and his colleagues, Sunderland (1946) has published other figures for the level of entry of motor nerves, based on 20 dissections each of the radial, ulnar median and sciatic nerves. The wide variation in levels noted by the previous authors was again found and the limits of these variations were indicated by Sunderland and his colleagues.

Sunderland (1947) also made a critical analysis of much of the work discussed above he raised objections to the methods employed in these experiments, especially to the assumption that the rate of advance is constant. He criticized the work of Seddon and his colleagues on the grounds that their calculations were made from unreliable and inadequate anatomical data. Sunderland and his collaborators have collected more human anatomical data, on which greater reliance may be placed, and have calculated various rates of recovery (Sunderland 1946 1947 Sunderland and Hughes, 1946 a, b Sunderland and Ray 1946).

In this work Sunderland attempted to determine the rate of advance of *functionally mature motor fibres*" by considering the times taken for the recovery of two muscles whose shortest distances from a point on the nerve proximal to the site of origin of its first branch" had been measured The rate of advance was taken as the ratio of the difference between these distances and the difference between the times. This calculation was repeated for successive segments of the nerve and a set of rates obtained. Various assumptions are implicit in this method and these will be discussed later (p 24). It may be noted immediately that, while a constant rate of advance is not assumed for the whole nerve, such an assumption is made for each successive segment of the nerve these segments of course, are of varying lengths.

It is preferable to avoid a consideration of rates of recovery and to consider rather only the lapse of time between the injury or suture and the first sign of the recovery of voluntary activity in the different muscles. Since a large number of suitable cases was available at the end of the war it seemed worthwhile to make another investigation of the problem using Sunderland s anatomical data and a different statistical approach (Bowden and Sholl 1950) The aims of this survey were to see if it were possible to obtain more precise knowledge of the time-course of recovery after lesions of the radial nerve in man. Particular attention was paid to the time at which the process of functional recovery apparently began, the effect of the type and level of the lesion (cf Stopford 1920) and the effect that delay and length of resection had upon the rate of recovery after suture. An attempt was also made to see whether the final degree of recovery was related to the signs of advance of recovery

The histories and records of examination of all the radial nerve injuries treated at the Oxford Nerve Injuries Centre were examined Owing to the difficulties of obtaining complete records of clinical cases, especially where repeated examinations were required many had to be discarded For this investigation follow-up examinations were made at intervals of 1 to 2 weeks according to circumstances. The minimum requirements were considered to be a knowledge of the level of the lesion and complete records of the times at which voluntary contractions were first found in the different muscles. Clearly only those cases in which some recovery in all or most of the muscles normally supplied by the radial nerve could be observed were suitable for this enquiry In the cases of suture, the interval between injury and operation and the length of resection had to be known A final assessment of recovery was made and information was sought about the type and duration of physiotherapy Only cases of complete lesions which fulfilled these requirements were admitted for analysis. The methods of clinical examination have been described by Seddon (1949a) the level of the lesion in relation to the lateral epicondyle was found as accurately as possible by inspection of wounds, from radiographs in closed fractures and by palpation of a neuroma A fair proportion of cases was followed systematically by a single observer but all the examiners had received similar training and the methods they used were standardized as far as possible. The times at which the first sign of movement in each muscle was detectable were recorded and the grading of voluntary power recommended by the Medical Research Council was used if more than a flicker of movement was present, the observation was discarded for the purpose of this study since it was assumed that voluntary contractions must have appeared some considerable time before that particular examination

There were only 17 cases of suture and 14 of lesions in continuity that fulfilled the requirements of this study For brevity the distance of the lesion or the line of suture from the lateral epicondyle is referred to as the level of lesion If above this point, it is indicated as positive if below negative. The interval between the time of injury and suture is called delay Since the level of the lesion is known it is possible to calculate the distance from the lesion or suture to the most distal muscle showing recovery by using the anatomical data in each case The data are summarized in Tables 4 and 5

For every patient a plot was made indicating the distance recovered at given times Without exception, the plotted points indicated that the process of recovery of function could be fitted by a curve of decreasing slope indicating

a decrease in rate of advance of recovery with time and distance Curves of t
form

$$y = a + b \log x$$

fitted the data well

The initial period before the apparent beginning of the process of functio
recovery was found to be less for lesions in continuity than for sutures. T
period was determined by extrapolation. The mean value for suture was 96 da
with a standard error of 11 days and for lesions in continuity the mean w
64 with a standard error of 6 days.

The distances at which recovery might be expected at 100 150 200 250 a
300 days were calculated. It was evident that no reliable average rate of recove
could be given for the rate decreases with time and differs from case to case a
in each there was an initial period whose duration could only be determin
by extrapolation However there was no doubt that the distances recovered
a given time were greatest in those cases of lesions in continuity which ultimate
made a complete motor recovery these were probably cases of uncomplicat
axonotmesis

The recovery of function in the proximal muscles of each case was consider
and it was then possible to make a composite plot of the times at which recove

TABLE 4

Cases of suture of radial nerve

Case	Age (years)	Type of injury	Level of suture above lateral epicondyle (cm.)	Delay before operation (days)	Length of resection (cm.)	Distance from suture line to most distal muscle showing recovery (cm.)	Galvanism	Fi rec
R7	18	Laceration	−3 0	74	4·0	11	0	M5
R55	25	G.S.W *	+2 4	57	6·3	19	+	M3
O8	31	Compound sepsis*	+3 0	235	4 7	20	+	M4
A59	20	G.S W	+4·0	129	6·0	21	+	M4
B77	30	G.S.W	+8 5	127	3 0	25	+	M4
M8	27	G.S W	+9 0	307	3 0	25	+	M4
F26A	22	G.S.W	+10 0	263	5·7	27	+	M2
T39	30	Compound	+10 0	161	2 7	26	+	M2
H53	23	G.S.W	+11·0	293	3 5	28	†	M4
G47	26	G.S.W *	+12·0	231	3 2	29	+	M4
B63	41	Compound	+12·0	283	1 5	29	0	M3
B145	31	G.S W	+14·0	70	2 2	31	+	M4
L41	29	G.S.W	+14 5	223	5·3	31	+	M4
J(TA)	21	G.S.W	+15 0	188	2 5	32	+	M3
F2	25	G.S.W *	+17·0	377	7·0	34	0	M4
P35	21	G.S W (Brachial artery severed)	+18 0	217	3·0	35	+	M3
B84	27	G.S W	+20·6	192	3 7	38	†	M4

Fracture of humerus
+ Galvanism given
0 Galvanism not given
† Galvanism employed irregularly

was noted and of the distances between the lesions and the proximal muscles in all cases. From these data confidence limits were calculated for the distance over which the recovery of voluntary activity could be expected at a given time These limits were found to be so broad that it is clear that when clinical con ditions suggest the desirability of exploration operation should not be delayed For example, 150 days after the injury the confidence limits ranged from 3 cm to 30 cm when there was a lesion in continuity at 12 cm. above the lateral epicondyle of the humerus For sutures at the same levels and after the same time, the confidence limits ranged from 0 cm to 21 cm Where the lesion or suture was at a greater distance above the epicondyle the limits were broader Thus, where there is any reasonable doubt about the state of the nerve or the integrity of a suture line, it may be unjustifiable to delay exploration until the confidence limits have been passed

TABLE 5

Cases of radial nerve lesions in continuity

Case	Age (years)	Type of injury	Level of lesion above lateral epicondyle (cm.)	Distance from lesion to most distal muscle showing recovery (cm.)	Galvanism	Final recovery
A22	21	G.S.W	+4	21	‡	M5 S4
L10	25	Fracture	+10	27	0	M5 S4
H81	21	Fracture	+12	29	+	M5
E19	23	Strep. poly neuritis	+18	35	+	M5
B1	63	Dislocation of shoulder	+36	51	0	M5 S3
P20	36	Fracture	+12	29	0	M4 S2
P11	30	Fracture	+12	26	0	M4 S2
H110	33	G.S.W and fracture	+14	31	+	M4 S3
A10	20	G.S.W	+15	31	+	M4 S2
B5	29	G.S.W and fracture	+17	34	‡	M3 S3
C118	22	G.S.W	+20	37	0	M4 S2
J29	70	Dislocation of shoulder	+29	46	+	M4 S4
F49	18	Traction	+30	47	+	M3 S4
M23	35	G.S.W	+38	54	0	M4 S2

‡ No record

The level of the lesion affected the distance recovered in a given time the rate being more rapid with the higher lesions this effect increased with the time after suture or injury (Fig. 11) In this investigation the delay before suture and the length of resection had no apparent effect upon the rate of advance of recovery However in this series the delay was less than 200 days in half the cases and in only one did it exceed 300 days, and in no case did the resection exceed the critical value of 7 5 cm found by Zachary (Seddon 1949a see also p 388) Where the level of the lesion delay and length of resection were

considered together they were found to have a more pronounced effect than the level of the lesion alone.

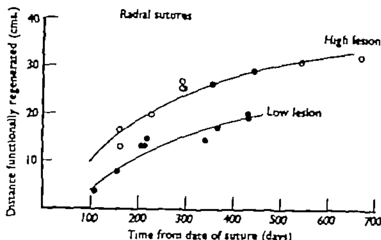


FIG 11 Graph showing progress of return of voluntary power after repair of high and low lesions of the radial nerve.

4 Conclusions

There is evidence to show that in man and animals the nature of the lesion in the nerve trunk influences the rate of outgrowth of axon tips, and the rate of advance of recovery of function These rates are more rapid after a simple crush injury than after a suture of the nerve or an extensive lesion in continuity The choice of time for exploration of an injured nerve cannot be based on estimates of rates of recovery alone in each individual case all clinical factors must be taken into consideration. Where there is any reasonable doubt about the state of the nerve or the integrity of a suture line, operation should not be delayed since in experienced hands exploration is without harmful effect.

There is an initial delay before the axon tips reach the distal stump of the nerve, and there is a longer delay before there is clinical evidence of functional recovery This initial delay and the delay before recovery of function are shorter after a simple crush injury than after a suture The relation between the time of recovery and the distance recovered involves a number of variable factors, and there is no single rate of recovery The different techniques of measuring rates have consequently given different results Over the relatively short distances involved in the rabbit, the rate of outgrowth of axon tips appears to be constant, and the same is generally true of the rate of recovery of function However there was an exception to this, for when the rate of shrinkage of analgesic areas was measured in the rabbit, it was found to decline with increasing distances and times

In man, where the distances involved are considerably longer there is a *progressive decline in the rate of outgrowth of axon tips* as measured by the advance of Tinel's sign and also in the rate of advance of recovery of function Not only is there a steady decrease in the rate of outgrowth of axon tips and recovery of function but there is also considerable variation between individual cases. The underlying causes of the variations have not yet been analysed fully but there is evidence to suggest that the level of the lesion plays a significant part in that the higher the lesion, the more rapid appears to be the progress of recovery In view of the declining rate of recovery and the wide variations which have been found it is not possible at present to find a useful and reliable figure for the average rate of recovery The average rates found by Seddon *et al* (1943) and by Napier (1949) can be used only with reserve as rough approximations.

PART III VASOMOTOR AND NUTRITIONAL DISTURBANCES AFTER INJURIES TO PERIPHERAL NERVES

by R. L. RICHARDS

1 Introduction

IT IS a common clinical observation that injury to a peripheral nerve may be followed by changes in the vasomotor and nutritional states of the parts supplied by that nerve Hitherto the nutritional changes have been referred to as trophic changes and their pathogenesis has been imperfectly understood It is still undecided whether these so-called trophic changes are due to the distur bance of some specific trophic function exerted by a nerve upon the tissues which it supplies, or whether they are secondary to the motor sensory and autonomic disturbances which follow nerve injury The literature on peripheral nerve injuries, from the pioneer work of Weir Mitchell and his colleagues during the American Civil War of 1861–5 and that done up to the outbreak of the Second World War in 1939 gives little information on the subject of trophic changes but certain facts appear to be established After nerve injury vasomotor and nutritional changes are by no means constant they are more often associated with lesions of those nerves which are responsible for the major sensory supply to the hand and foot (median internal popliteal) than with lesions of predominantly motor nerves (radial lateral popliteal) or sensory nerves supplying the forearm and leg (medial cutaneous of forearm, saphenous) Moreover even in cases where a nerve of the first type is injured the degree of trophic change is exceedingly variable incomplete and so-called irritative lesions are believed to be accompanied by the most severe disturbances.

The studies to be reported were made upon an unselected series of patients admitted to the Peripheral Nerve Injuries Centre at Gogarburn Hospital Edinburgh between June 1941 and February 1946 During this period approximately 1 100 cases were classified as having lesions of peripheral nerves. Patients were asked questions as a matter of routine about any objective or subjective disturbances which they had noticed in the temperature, colour and nutrition of the injured limb and at each examination a careful record of all vasomotor and nutritional changes was made. In certain cases the written record was supplemented by photographs

2. Vasomotor and Nutritional Disturbances observed after Injuries to Peripheral Nerves

In Tables 6 to 8* will be found data concerning vasomotor and nutritional disturbances obtained from a study of the case records of 388 patients with lesions of the main peripheral nerves of the limbs A simple classification into complete and incomplete lesions has been made. Complete lesions include all cases in which the clinical findings indicated that there was complete interruption of the nerve at the site of the lesion most of these cases had resection and suture performed. All other lesions are considered under incomplete lesions Cases of injury to the radial and lateral popliteal nerves have been excluded because few showed any marked vasomotor or nutritional disorders. Lesions of the brachial plexus and multiple nerve injuries with the

* The percentages in these and the other tables are only a convenient means of expressing the frequency of a finding and are not to be regarded as statistically precise.

TABLE 6

Incidence of vasomotor and nutritional disturbances complete lesions—all levels

Nerve	No. of cases	Clinical findings															
		Coldness		Warmth		Changes in						Digital atrophy		Ulcers, blisters, scars, etc.		Oedema	
						Skin colour		Skin texture		Nails							
		No.	%	No.	%	No.	%	No.	%	No.	%	No.	%	No.	%	No.	%
Median	55	40	73	5	9	40	73	38	69	39	71	49	89	27	49	1	1
Ulnar	108	60	56	17	16	67	62	90	83	59	55	79	73	28	26	4	4
Median and ulnar	17	9	53	5	29	14	71	16	94	14	71	17	100	4	24	3	17
Sciatic	31	14	45	15	48	21	68	28	90	18	58	15	48	19	61	21	68
Internal popliteal	28	10	36	8	29	13	46	21	75	12	43	14	50	7	25	6	21
Total complete lesions	239	133	56	50	21	155	65	193	81	142	59	174	73	85	36	35	15

Includes posterior tibial

TABLE 7

Incidence of vasomotor and nutritional disturbances incomplete lesions—all levels

Nerve	No. of cases	Clinical findings															
		Coldness		Warmth		Changes in						Digital atrophy		Ulcers, blisters, scars, etc.		Oedema	
						Skin colour		Skin texture		Nails							
		No.	%	No.	%	No.	%	No.	%	No.	%	No.	%	No.	%	No.	%
Median	31	13	42	4	13	13	42	14	45	22	71	26	84	5	16	0	
Ulnar	43	23	53	2	5	18	42	31	72	28	65	26	60	3	7	2	5
Median and ulnar	14	8		2		10		10		12		10		0		0	
Sciatic	41	13	32	20	49	21	51	25	61	17	41	19	46	3	7	13	32
Internal popliteal*	20	8	40	7	35	11	55	11	55	4	20	4	20	3	15	3	15
Total incomplete lesions	149	65	33	35	23	73	49	91	61	83	55	85	57	14	9	18	12

Includes posterior tibial

TABLE 8

Incidence of vasomotor and nutritional disturbances totals

Nerve		No. of cases	Clinical findings															
			Coldness		Warmth		Changes in						Digital atrophy		Ulcers, blisters, scars, etc.		Oedema	
							Skin colour		Skin texture		Nails							
			No.	%	No.	%	No.	%	No.	%	No.	%	No.	%	No.	%	No.	%
Upper limb	Median	86	53	62	9	10	53	62	52	60	61	71	75	87	32	37	1	1
	Ulnar	151	83	62	19	13	85	63	121	80	87	64	105	70	31	21	6	4
	Median and ulnar	31	17	55	7	23	24	77	26	84	26	84	27	87	4	13	3	10
Total for upper limb		268	153	57	35	13	162	60	199	74	174	65	207	77	67	25	10	4
Lower limb	Sciatic	72	27	37	35	49	42	58	53	74	35	49	34	47	22	30	34	47
	Internal popliteal	48	18	37	15	31	24	50	32	67	16	33	18	37	10	21	9	19
Total for lower limb		120	45	37	50	42	66	55	85	71	51	42	52	43	32	27	43	36
Grand totals		388	198	51	85	22	228	59	284	73	225	58	259	67	99	26	53	14

Includes posterior tibial

exception of straightforward lesions of both median and ulnar nerves have also been omitted Cases with associated injuries to the main blood vessels of the limb or with a major orthopaedic lesion in addition to the nerve injury have been excluded in order that the findings might be assessed in terms of the nerve lesion alone.

(i) *Changes in Temperature of Skin*

(*a*) *Subjective* As a general rule the patient complained that the affected limb felt subjectively colder than its fellow the coldness might be referred to the particular area supplied by the injured nerve or nerves *but equally frequently* it was stated that the entire extremity was cold Coldness of the limb was a more frequent complaint in lesions of the upper than of the lower limb It was comparatively rare for a patient to complain that the affected limb or a portion of it was abnormally warm but when such a statement was made one of three *sets of circumstances was usually present (i) the nerve injury* was of recent date (ii) the nerve injury was associated with pain which might or might not have the characteristics of causalgia and (iii) the nerve affected was the sciatic or one of its divisions. An observation made by more than one intelligent patient was that in a warm environment the affected hand or foot would be abnormally warm and in a cold environment abnormally cold as one patient aptly put it, It seems to go to extremes

(*b*) *Objective* As can be seen from the data in Tables 6 and 7 objective *evidence of coldness of the affected limb was present in only one half of the* cases considered It is worth noting, however that the incidence of coldness was greater in complete lesions (about one half) than in incomplete lesions (one third), and that it was also greater in lesions of the nerves of the upper than of the lower limb The incidence of coldness was greatest in lesions of the median nerve.

Increased warmth of the affected hand or foot was less frequently observed than coldness, the incidence in the series being only about one in five There was no difference between complete and incomplete lesions in this respect, but the incidence of increased warmth was three times as common in lesions of nerves of the lower than of the upper limb It has already been indicated that many of the patients who complained of abnormal warmth of the affected extremity had either a recent nerve injury or a lesion associated with pain the influence of these factors upon the objective vasomotor disturbances *will be considered later*

In most of the cases palpation was sufficient to determine whether there was any difference in temperature between the parts affected by the nerve lesion and the rest of the extremity or the corresponding area in the normal limb 'There is no better method of quickly ascertaining that one limb is cooler than its fellow in its length or of ascertaining the extent of an area of relative coolness or warmness, than by feeling the relevant skin areas" (Lewis 1946) Accurate measurement of skin temperature by thermojunctions or other means provides absolute data which confirm clinical observations (see Fig. 31) Although the area of temperature change was often confined to the autonomous zone of the injured nerve, it was not unusual for the entire hand or foot to be relatively cold This was especially true with lesions of the ulnar nerve when the whole hand was often colder than its fellow Only rarely was there an abrupt change in tempera ture between the normal and the abnormal skin.

The influence of environmental temperature on that of a denervated area of skin was frequently observed In the winter months coldness of the affected

extremity was often striking, whereas in the summer little difference might be detected between the temperature of normal and abnormal parts

(ii) *Changes in Colour of Skin*

Few patients were conscious of any change in the colour of the skin of the affected part, and yet colour changes were observed in one half of them. The incidence of such changes was a little greater in complete than in incomplete lesions but there was little difference as between the upper and lower limbs.

The usual colour changes were cyanosis and redness, generally confined to the territory supplied by the injured nerve and often showing a clear line of demarcation which corresponded closely with the boundary of the zone of analgesia to pinprick (Figs 12 and 13) Cyanosis and redness were frequently observed in the same case on different occasions, and, when associated with coldness, these colour changes represent a slow or arrested circulation through the cutaneous blood vessels, the degree of cyanosis or redness depending upon the state of oxygenation of the blood in these vessels Pallor was less common and was more frequently noted in the foot in cases of injury to the sciatic nerve than with nerve lesions in the upper limb The occurrence of cyanosis or redness in association with increased warmth of the affected parts was rare and could usually be attributed to the presence of some infective process in the denervated area (see p 33) In cases with increased warmth, colour changes were often minimal the warm and pink skin indicating a rapid flow of well-oxygenated blood through the cutaneous vessels

(iii) *Changes in Texture of Skin*

Changes in the texture and general appearance of the skin supplied by an injured nerve were seen in three quarters of the cases observed. The incidence was higher in cases with complete lesions (81 per cent) than in those with incomplete lesions (61 per cent) The frequency in the upper and lower limbs was the same.

In the first few days after injury to a nerve the skin supplied by the injured nerve showed a tendency to scaliness and desquamated readily (Fig. 14) leaving smooth rather atrophic, skin This smoothness of the skin was the most frequent change seen in well-established cases of nerve injury and varied from a slight degree of smoothing which was most marked in the acral parts to the extreme form, glossy skin that was so well described by Paget, Mitchell *et al* Bowlby and other writers of the 19th century (Figs. 15 and 18) Yet even in cases of well-marked glossy skin some trace of the ridges and papillae of the skin remained and it was still possible to detect the whorls, loops and other features of the finger prints Some cases showed a tendency persisting for weeks or months, to hyperkeratosis with excessive desquamation of the skin. Other changes in the skin will be considered later (p 33)

(iv) *Changes in Nails and Hair*

Alterations in the growth and appearance of the nails are frequently observed in association with peripheral nerve injuries. Rather more than half of the patients showed some abnormality of nail growth the incidence of changes being slightly greater in cases with complete lesions than with incomplete lesions and also greater in lesions involving the nerves of the upper than of the lower limb

As with other disturbances of nutrition, changes in the nails varied in degree. At one extreme were the long, curved talon like nails seen in combined median

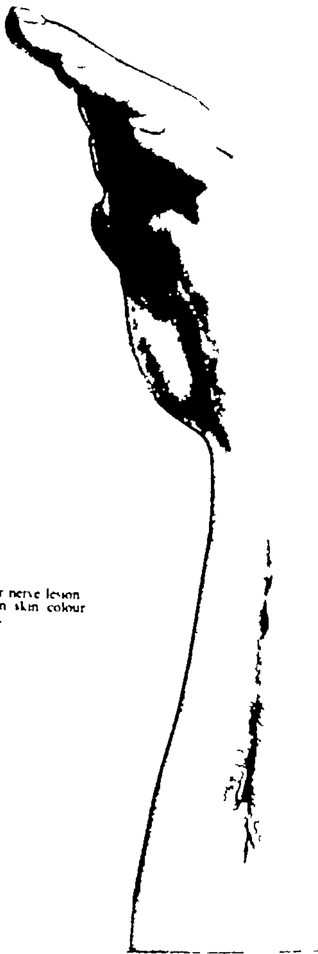


Fig. 12. Left ulnar nerve lesion showing change in skin colour in denervated area.



Fig. 13 Right median nerve lesion showing change in skin colour in denervated area.



Fig. 14 Left median nerve lesion (4 weeks after injury) showing changes in skin texture in first 3 digits.

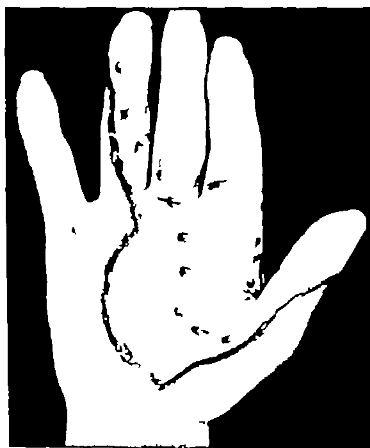


Fig. 15 Right median nerve lesion showing areas of anaesthesia (——) and analgesia ( ) and marked atrophy of skin and subcutaneous tissue in thumb index and middle fingers.



FIG 16. Left median and ulnar nerve lesions showing talon-like nails.

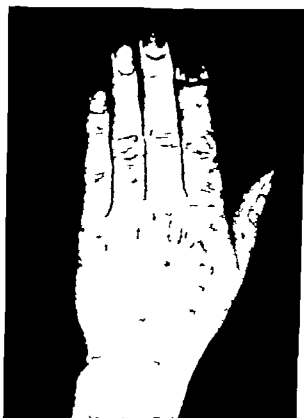


FIG. 17 Left median nerve lesion showing irregularity of nail growth in index finger as the result of a paronychia.

and ulnar lesions (Fig. 16) and at the other a minimal increase in curvature of the nail of the little finger in ulnar palsy Typically the nails lost their lustre became dry and brittle exhibited an increase in the degree of curvature in both directions and showed other irregularities such as transverse ridges grooves and humps The cuticle tended to disappear and the skin to retract from the base of the nail In most cases nail growth was retarded but in a minority there appeared to be a definite acceleration The changes were usually confined to the nails of digits supplied by the injured nerve, but it was not uncommon to see a case in which all the finger nails showed a disturbance of their growth although only one nerve (median or ulnar) had been affected Nail bed infections were relatively common in insensitive digits and might lead to loss of the nail and to further irregularities of growth which could not be attributed directly to the nerve lesion (Fig. 17) Changes in nail growth were more common in the finger nails, but they did occur and might be quite severe in the toe nails (Fig. 18)

Both hypertrichosis and loss of hair have been described as accompaniments of nerve lesions. An apparent increase in the amount of the hair in the forearm and leg in association with lesions of the median and ulnar and sciatic nerves respectively was often due to the marked wasting of muscles. No constant alteration in hair growth was observed but it was noted in some cases with lesions of the median and ulnar nerves that the hairs on the back of the fingers became shorter stouter more brittle and did not lie flat across the fingers as in the normal hand (Fig. 19)

(v) *Digital Atrophy*

Atrophy of the subcutaneous tissue of the digits is a well recognized accompaniment of lesions of the median nerve and also occurs in lesions of the other major nerves. In the present series the total incidence of the finding was 67 per cent, with a greater incidence in complete than incomplete lesions and nearly twice as frequent in cases where the nerves of the upper limb were injured than in those with injury of the nerves to the foot. In complete lesions of both median and ulnar nerves all cases showed the phenomenon and of the individual nerves both complete and incomplete lesions of the median had the highest incidence

The atrophy varied greatly from the tapered index finger so characteristic of a median palsy (Figs. 15 and 20) to a degree of atrophy in the little finger in an ulnar lesion that was so slight as not to be appreciable unless the circumference of the finger was measured With practice, a high degree of accuracy could be reached in assessing the presence or absence of digital atrophy by visual comparison of the digit with its normal fellow but it was not until the last few months of the study that the practice was adopted of measuring those fingers which did not appear to show atrophy It was then found that minor degrees of atrophy were being overlooked and so the figures for the incidence of digital atrophy are probably too low especially for lesions of the ulnar nerve. Measurement also revealed that although atrophy was always greatest in the terminal segment of an affected digit, the more proximal segments also showed some degree of atrophy

Case PN 800 Complete Division Left Ulnar Nerve

	Circumference of little fingers (mm)	
	Right	*Left*
Proximal phalanx	57	49
Middle phalanx	50	42
Distal phalanx	47	40



FIG 18 Left sciatic causalgia showing changes in nail growth in toes and alterations in skin colour and texture in affected foot.

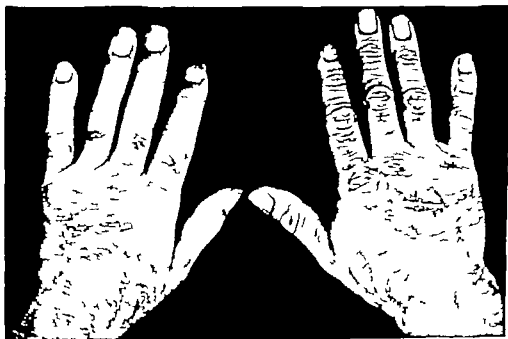


FIG. 19 Left median nerve lesion showing alterations in skin, nails and hair in fingers.

In cases of injury to the sciatic and internal popliteal nerves, atrophy of the pads of the toes was more difficult to assess, but it was sometimes striking particularly in the great toe. There was no doubt that the incidence of digital atrophy was less in the toes than in the fingers and the reasons for this will be discussed later

(vi) *Ulcers Blisters and other Similar Lesions*

Tissues which are deprived of their nerve supply are particularly prone to ulceration and the development of other so-called trophic lesions Twenty six per cent of all cases showed some form of ulcer or blister or had scars which from the history were undoubtedly the relics of such lesions In cases in which the nerve was completely interrupted the incidence of lesions of this type was about one third of the total whereas in incomplete nerve lesions it was only about one in ten There was no significant difference between the frequency of lesions of this type in the upper and lower limbs Of individual nerves complete lesions of the sciatic nerve had the highest incidence and the median nerve came next.

Certainly in most cases and probably in all trauma was the most important factor in causing ulcers and blisters. Such lesions occurred most frequently on those parts of the limbs which were most liable to injury the palmar aspect and outer borders of the fingers, the dorsum of the toes and the weight bearing portions of the foot It was not always possible to elicit a history of trauma, because on account of the loss of sensibility the patient might have been unaware of it. In the upper limb cigarette burns were probably the commonest single cause, with burns due to domestic appliances (teapots, hot pipes, stoves etc.) second (Fig. 21) In the lower limb poorly fitting footwear and trauma to the foot when walking were the most frequent causes (Figs. 22 and 23) Ulcers on the hand or fingers were usually shallow and the writer agrees with Doupe and Cullen (1943) that such lesions are accompanied by the classical vascular response of inflammation and that, if properly treated they heal rapidly and well In the foot, because of the greater incidence of oedema (see below) and the tendency for the same injury to be repeated, it was more difficult to keep ulcers soundly healed, and as a result they tended to become deep and might involve bone especially in the regions of the heads of the first and fifth metatarsals, thus forming the typical perforating ulcer

Another common type of ulcer was that which developed on the dorsal aspect of the digits in the region of the nail These were the result of a paronychia which led to the loss of the nail and might in turn lead to irregularities of nail growth not directly due to the nerve lesion (see above)

Under this heading also it is pertinent to consider those cases in which there were recurrent crops of watery blisters in the area supplied by an injured nerve Lesions of this type have been described previously chiefly in association with causalgia and there is no unanimity as to their cause (Doupe and Cullen 1943) Only four cases showed lesions of this type All were cases of injury to nerves of the upper limb brachial plexus one (Fig. 24) median two and ulnar one. The ulnar lesion and one of the median lesions were complete divisions of the nerve the other two were incomplete lesions. In none was pain a prominent feature. In one of the cases the possibility that the lesions on the palm might have been due to the *Sarcoptes scabiei* which was present elsewhere in the body could not be excluded but in the other three no such possibility arose Excessive sweating of the hand was noted in these three cases.



FIG 20 Right median nerve lesion showing area of anhidrosis (quinizarin method) and marked tapering of index and middle fingers.



FIG 21 Right median and ulnar nerve lesions burns of finger tips from handling hot teapot.



FIG 22. Right sciatic nerve lesion superficial burn of sole from hot water bottle.



FIG 23 Left posterior tibial nerve lesion pressure sores from badly fitting footwear

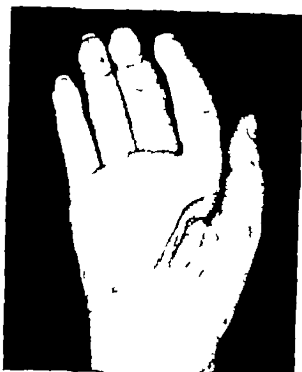


FIG. 24 Right brachial plexus lesion herpetic eruption over palm and fingers.

(vii) *Oedema*

The incidence of oedema was almost negligible in those cases in which the nerves of the upper limb were involved (4 per cent) In lesions of the nerves of the lower limb the total incidence was about one third and in complete lesions of the sciatic nerve swelling of the foot was noted in two thirds of the cases

(viii) *Other Lesions*

A few patients with lesions of the median nerve complained that in cold weather they developed chilblains on the insensitive digits, and in at least one patient lesions were observed which were clinically indistinguishable from the ordinary chilblain In a number of cases of long standing lesions of the ulnar nerve a condition like Dupuytren s contracture has been seen Wexberg (1935a) mentioned that this occurred in median lesions but in the present series it has been noted only in ulnar lesions.

3 Factors Influencing the Incidence and Severity of Vasomotor and Nutritional Disturbances

(i) *The Injured Nerve*

It has already been pointed out that the occurrence of vasomotor and nutritional changes is inconstant after nerve injury and that such changes depend to some extent upon the nerve which is injured It is now necessary that these statements be examined more critically in relation to the data presented above The cases selected for study were those in which, from a study of the literature and from personal experience, a high incidence of vasomotor and nutritional changes was expected. Of the changes studied the greatest incidence

of any one was about three out of four (changes in skin texture) coldness changes in skin colour changes in the nails and digital atrophy all occurred in about half the cases On comparing the findings for individual nerves (Table 8 p 26) there is considerable agreement in the incidence of the various changes in the case of lesions of the median and ulnar nerve on the one hand and lesions of the sciatic and medial popliteal nerves on the other The latter finding is not altogether unexpected since vasomotor and nutritional disturbances following injury to the sciatic nerve are thought to be due mainly to the lesion of the medial popliteal component In the case of the median and ulnar nerves, however the close correspondence between the figures is surprising since the median nerve is much the more important nerve of the two so far as the sensory and probably the autonomic, nerve supply to the hand is concerned Only changes in the nails, digital atrophy and ulcers show a higher incidence in lesions of the median nerve. These findings are thought to be most significant and they will be discussed in more detail when the pathogenesis of the vasomotor and nutritional disturbances is considered

(ii) *Nature of Lesion*

A comparison of the data set out in Tables 6 and 7 (p 26) and a study of Figs. 25 26 and 27 show that the incidence of vasomotor and nutritional changes is higher in complete than in incomplete lesions. Only two of the phenomena studied have a higher incidence in incomplete lesions abnormal warmth in median nerve lesions and nail changes in ulnar nerve lesions. For all other

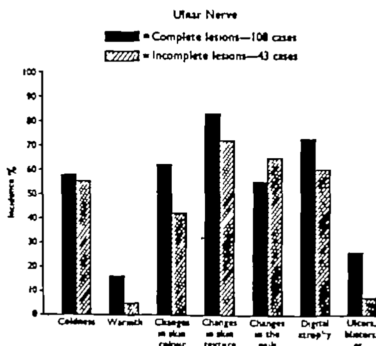


FIG 25 Ulnar nerve histogram comparing incidence of vascular and nutritional disturbances in complete and incomplete lesions.

disturbances the incidence is either approximately the same in the two types of lesion or significantly less in the case of incomplete lesions This is a surprising finding since previous writers are almost unanimous in either stating or implying that trophic changes are more frequent and more severe in incomplete lesions. The contradictory results of the present study might be explained if a large number of cases in which damage to the nerve was minimal had been included

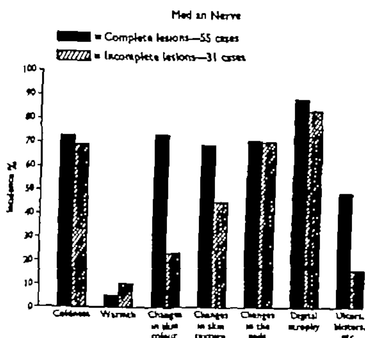


FIG. 26. Median nerve histogram comparing incidence of vasomotor and nutritional disturbances in complete and incomplete lesions.

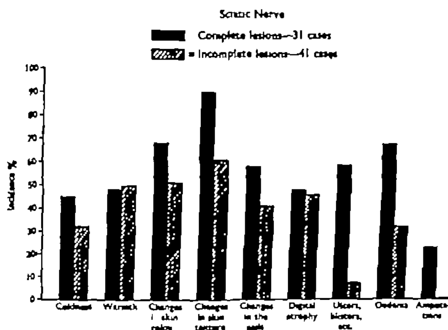


FIG. 27 Sciatic nerve histogram comparing incidence of vasomotor and nutritional disturbances in complete and incomplete lesions.

in the incomplete lesions but this is not the case only cases with a definite nerve injury were included. This accounts for the number of incomplete lesions being smaller than that for complete lesions had all cases showing incomplete lesions been included the number would have been much larger and the incidence of vasomotor and nutritional disturbances even less. It is therefore justifiable to conclude that the incidence of vasomotor and nutritional disturbances is

significantly greater in complete as compared with incomplete lesions Since there is no satisfactory method by which the severity of such changes may be graded it is more difficult to decide whether such changes are also more *severe* in complete lesions Nevertheless there was no doubt in the minds of all the medical officers responsible for the care of the patients that the most severe vasomotor and nutritional changes were observed in those who had completely divided nerves and particularly *in those patients with complete lesions of both median and ulnar nerves The high incidence of all objective findings in such* cases is indicated in Table 6 (p 26) and lends support to this opinion

(iii) *Level of Lesion*

Does the site of a lesion along the course of a nerve influence the incidence of the vasomotor and nutritional disturbances? In considering this question only data obtained from the cases with lesions of the median and ulnar nerves will be analysed The cases were first divided into groups consisting of high inter mediate and low lesions as follows

Median Nerve

(*a*) High lesions—in the arm proximal to all branches
(*b*) *Intermediate lesions—between (a) and (c)*
(*c*) Low lesions—distal to the origin of the anterior interosseous nerve.

Ulnar Nerve

(*a*) High *lesions—more than 5 cm above the medial epicondyle.*
(*b*) Intermediate lesions—between (*a*) and (*c*)
(*c*) Low lesions—distal to the branches to flexor digitorum profundus.

In the case of the median nerve the numbers of high and intermediate lesions were too small to be of value so they have been considered together and compared with the low lesions

The incidence of vasomotor and nutritional changes in these groups of cases is *shown in Tables 9 and 10 and in Figs. 28 and 29 It will be seen that in the case* of the ulnar nerve the incidence is approximately the same for high, inter mediate and low lesions. In the case of the median nerve the incidence of all the changes studied is higher in the high plus intermediate lesions. This finding is unlikely to be due to the fact that there is a greater proportion of incomplete lesions in the high plus intermediate group because, as shown above, the

TABLE 9

Influence of level of lesion on vasomotor and nutritional disturbances ulnar nerve (151 cases)

Level of lesion	No. of cases	Clinical findings															
		Coldness		Warmth		Changes in						Digital atrophy		Ulcers, blisters, scars, etc.		Oedema	
						Skin colour		Skin texture		Nails							
		No.	%	No.	%	No.	%	No.	%	No.		No.	%	No.		No.	%
High	25	15	60	2	8	14	56	19	76	16	64	18	72	4	16	1	4
Intermediate	73†	40	55	11	15	45	62	60	82	37	51	47	64	18	25	2	3
Low	53‡	28	53	6	11	26	49	42	79	34	64	40	75	9	17	3	6

Includes 24 per cent incomplete lesions
† Includes 30 per cent incomplete lesions
‡ Includes 28 per cent incomplete lesions

TABLE 10

Influence of level of lesion on vasomotor and nutritional disturbances median nerve (86 cases)

Level of lesion	No. of cases	Clinical findings													
		Coldness		Warmth		Changes in						Digital atrophy		Ulcers, blisters, scars, etc.	
						Skin colour		Skin texture		Nails					
		No.	%	No	%	No.	%	No.	%	No.	%	No.	%	No.	
High plus intermediate	36	24	67	4	11	29	80	25	69	31	86	34	94	16	44
Low	50†	29	58	5	10	24	48	27	54	30	60	41	82	16	32

Includes 44 per cent incomplete lesions
† Includes 30 per cent incomplete lesions

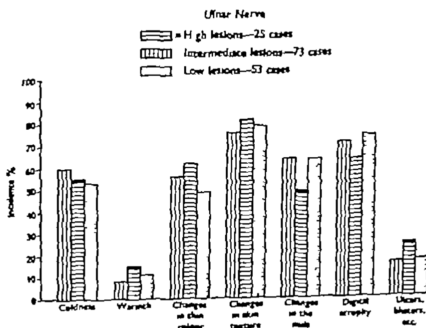


FIG. 28 Ulnar nerve histogram showing influence of level of lesion upon incidence of vasomotor and nutritional disturbances.

incidence of changes is smaller in the incomplete lesions and thus a higher proportion of such lesions in any group should tend to lower rather than raise the incidence of vasomotor and nutritional changes in that group.

Since it has been found impossible to devise a method for measuring the severity of vasomotor and nutritional disturbances it is difficult to be dogmatic regarding the influence of the level of the lesion upon the severity of these changes. However it is the writer's impression, and one which is shared by others, that in the case of the median nerve more severe nutritional changes are seen in patients who have high lesions of the nerve whereas in the case of the ulnar nerve equally severe disturbances are seen with lesions at all levels. It is therefore suggested that there is evidence that the incidence and severity of

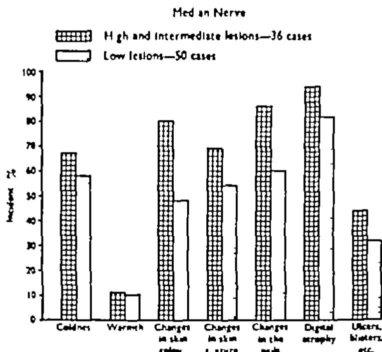


FIG 29 Median nerve histogram showing influence of level of lesion upon incidence of vasomotor and nutritional disturbances.

vasomotor and nutritional changes are both greater in high than low lesions of the median nerve whereas in the case of the ulnar nerve the level of the lesion makes little difference. These findings are thought to be significant and will be discussed further when considering the problem of pathogenesis (p 52)

(iv) *Age of Lesion*

The motor and sensory paralyses which follow damage to a peripheral nerve are maximal immediately after the injury In the succeeding weeks the tendency is towards recovery either due to regeneration if the nerve is not completely divided or to the effects of overlap from adjacent intact nerves However injury to a nerve does not at once result in the development of all the vasomotor and nutritional disturbances which have been described Indeed they are not seen in their more florid forms until some weeks if not months have elapsed It is therefore important to consider the age of the nerve lesion that is to say the interval between the injury and the date of the examination as one of the factors which may be expected to influence the incidence and severity of the vasomotor and nutritional disturbance

Immediately after division of a peripheral nerve a well-defined area of skin corresponding approximately to the area of cutaneous analgesia, becomes hot, flushed and dry This is a well recognized phenomenon and has been described by numerous writers (Lewis and Pickering, 1936 Atlas 1938 Richards, 1943) For a short period the affected area remains warm and its temperature relatively independent of that of the environment Then a gradual transition takes place and the temperature of the affected area becomes dependent upon that of the environment which in the United Kingdom at any rate means that it is usually colder than the corresponding normally innervated area (pps 27 45) It has therefore been suggested that the vasomotor effects of nerve division can be arbitrarily divided into an initial brief warm phase and a late prolonged cold phase (Richards 1943)

Only 18 patients were seen within one month of the date of injury This small number was due to the fact that most of the patients were battle casualties and did not reach the Nerve Injuries Centre until some time after being wounded The vasomotor and nutritional changes observed in these 18 cases at the initial examinations are set out in Table 11 It will be noted that in 14 of these cases the affected area was palpably warmer than the corresponding normal area. Of the remainder no difference in temperature could be detected in two and in two cases the affected area was the colder Of these four cases only one (Case 1) was examined less than 21 days after wounding.

TABLE 11

Vasomotor and nutritional disturbances in cases seen within 30 days of injury Objective findings

Case	Nerve	Warmth	Coldness	Changes in			Digital atrophy	Ulcers, etc.	Interval (days)
				Skin colour	Skin texture	Nails			
1	Ulnar	–	+	–	+	–	–	–	9
2	Ulnar and median	+	–	–	+	–	+	–	30
3	Ulnar and median	+	–	–	+	–	–	+	15
4	Ulnar	+	–	+	+	–	–	–	12
5	Ulnar	+	–	+	+	–	–	+	30
6	Ulnar and median	+	–	+	–	–	–	–	11
7	Ulnar	+	–	–	+	–	–	–	16
8	Ulnar	+	–	+	+	–	–	–	7
9	Ulnar	+	–	+	+	–	–	+	6
10	Ulnar	–	–	+	+	–	–	–	25
11	Ulnar	–	+	+	+	–	–	–	30
12	Ulnar	+	–	+	+	–	–	–	23
13	Ulnar	+	–	+	+	–	–	+	18
14	Ulnar	–	–	–	+	–	–	–	27
15	Ulnar	+	–	+	+	–	–	+	5
16	Median	+	–	–	–	–	–	–	26
17	Sciatic	+	–	+	+	–	–	–	15
18	Ulnar	+	–	–	–	–	–	–	2
	Totals	14	2	11	15	0	1	5	

During this early period the warmth of the affected part was the striking feature but as shown in Table 11 changes in the colour and texture of the skin appeared soon after injury and their incidence was relatively high Digital atrophy and changes in the nails were not present. The latter was not observed in any of the 18 cases and a slight degree of digital atrophy was noted in only one case (Case 2) first seen 30 days after wounding. Ulcers were present in five of the 18 cases, an incidence which is slightly higher than that for the whole series (Table 8 p 26) This high incidence is almost certainly due to the fact

that during the first few weeks after injury patients have not yet realized how easily they may injure the insensitive area without knowing that they have done so

Observations on these 18 cases indicated that the transition from the warm to the cold phase was never abrupt and that the length of time that the warm phase lasted varied considerably Lewis and Pickering (1936) stated that in a case of ulnar nerve palsy the digits became cold between the third and twenty first day after injury Doupe (1943a) quoted another case also with an ulnar nerve lesion in which the first tendency to coldness was noted on the seventeenth day after injury In most cases in which the nerves of the upper limb are injured the transition certainly occurs at about three weeks after injury As the onset of the cold phase is due to the temperature of the affected area becoming dependent upon that of its environment it is possible for a denervated area to remain warm for much longer than 21 days if it is adequately protected from cold Since the foot is normally covered by a sock and some form of footwear it is not unusual to find that even six weeks to three months after a sciatic nerve injury the foot will still be warm This is reflected in the greater total incidence of warmth in the cases in which the nerves of the lower limb were involved (Table 8)

Once the cold phase is well established the other vasomotor and nutritional disturbances become more apparent and as already stated these changes are probably more marked in long standing lesions. In Table 12 a group of 86 injuries of the median nerve are analysed in terms of the age of the lesion those

TABLE 12

Influence of age of lesion on vasomotor and nutritional changes Median nerve

Age of lesion	No of cases	Clinical findings													
		Coldness		Warmth		Changes in						Digital atrophy		Ulcers blisters, etc.	
						Skin colour		Skin texture		Nails					
		No	%	No	%	No	%	No	%	No	%	No	%	No	
Early cases (less than 6 months)	44*	27	61	9	20	32	73	28	64	32	73	36	82	19	43
Late cases (more than 6 months)	42†	26	62	0	0	21	50	24	57	29	69	39	93	13	31

* Includes 32 per cent incomplete lesions and 50 per cent high lesions.
† Includes 40 per cent incomplete lesions and 33 per cent high lesions

less than six months old (early cases) being compared with lesions of longer duration (late cases) Unfortunately the numbers were so small that it was not possible to secure a group of cases in which the only variable factor was the age of the lesion both complete and incomplete and high and low lesions had to be included As has been shown both these factors influence the incidence of vasomotor and nutritional changes, and the fact that the early cases showed a lower proportion of incomplete lesions and a higher proportion of high lesions

has to be borne in mind when considering the results. Notwithstanding these difficulties the following deductions appear to be reasonable

1 An increase in temperature of the affected area is seldom if ever seen in late cases.
2. Changes in skin texture and in the nails are well developed by six months and thereafter their incidence seems to increase little if at all digital atrophy on the other hand, is more frequently encountered in late cases.
3 The incidence of ulcers blisters and other similar lesions is greater in the early months This is in keeping with the statement made above that these lesions are more frequent during the period when the patient has not yet learned to protect the insensitive area from trauma.

4 The Circulation in Denervated Areas

Before the outbreak of the recent war few accurate studies had been made on the circulation in parts deprived of their nerve supply In their classical monograph "On Gunshot Wounds and Other Injuries of Nerves Weir Mitchell, Morehouse and Keen (1864) described the use of 'the thermo-electric disks of M Becquerel in connexion with a very delicate galvanometer" to study "The Conditions of Calorification in Injuries of Nerves" They observed that a limb with an injured nerve was always colder than its fellow except in those cases associated with the burning pain which they later named causalgia From that date until the end of the 1914–18 war many clinical observers commented on the coldness of the parts affected by a peripheral nerve injury and described the nutritional disturbances, but no further vasomotor studies appear to have been made until Lewis and Pickering (1936) and Atlas (1938) studied the skin temperature of denervated digits and demonstrated the transition from the warm to the cold phase. Lewis and Pickering showed that the transition occurred at the same time as the axon reflex responsible for the triple response was lost. They also showed that when the cold phase was reached denervated digits did not respond to a rise in body temperature by vasodilatation During and since the recent war further vasomotor studies have been made by Doupe (1943a,b c), Doupe and Cullen (1943) Richards (1943 1946b), Schulenburg (1949) and others. The results of these observations may be summarized as follows

(i) *Observations on Skin Temperature*

The skin temperature gives a reasonably accurate indication of the state of the cutaneous circulation in the acral portions of the limbs. If two corresponding areas (e.g. two digits) are exposed to the same environmental temperature it is justifiable to conclude that any difference between their skin temperatures is due to a difference in circulation that is to say the circulation in the colder of the two areas is reduced (relative vasoconstriction) and in the warmer it is increased (relative vasodilatation) In cases of nerve injury observations of skin temperature almost invariably demonstrate a striking difference between corresponding normal and denervated areas. In early cases the denervated area is usually the warmer of the two (warm phase) and its temperature shows a remarkable degree of stability (Fig. 30) In late cases denervated parts are cold and tend to remain so (Fig. 31) When the affected extremity is exposed to extremes of environmental temperature the responses of denervated digits are quite different from those of normally innervated digits, whether the former be in the early warm phase (Fig. 32) or in the late cold phase (Fig. 33) In the

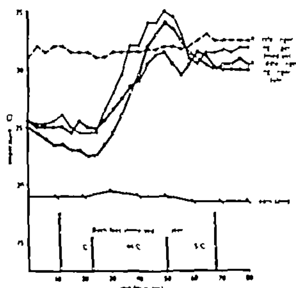


FIG 30 Patient A E., aged 19 (5 8 42) Vasomotor reactions of right hand Right ulnar nerve lesion (4 weeks after complete division) showing sustained vasodilatation in denervated little finger the temperature of which remains high and very stable.

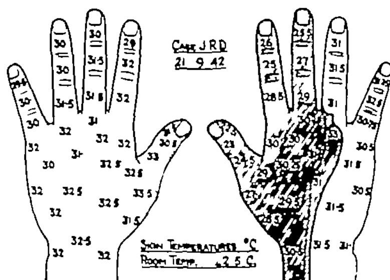


FIG 31 Right brachial plexus lesion note low skin temperature of insensitive area (shaded) compared with adjacent normal area and left hand.

warm phase the digit does not cool normally on exposure to cold but remains warm, whereas in the cold phase the digit cools more rapidly than the normally innervated digit and even after removal from the cold environment it tends to remain cold and warms very slowly compared with a normal digit In this latter state its responses resemble those of an inert body By recording the skin temperature around an ulcer blister or similar lesion occurring in a denervated area, as Doupe and Cullen (1943) have done it can be shown that the heat component of the classical triad of signs of inflammation occurs even in denervated tissues

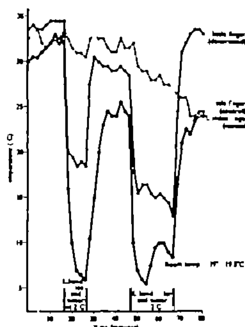


FIG. 32. Case J R., aged 24 (5.8.43). Left ulnar nerve lesion (14 days after complete division) showing reaction to low temperature of denervated digit.

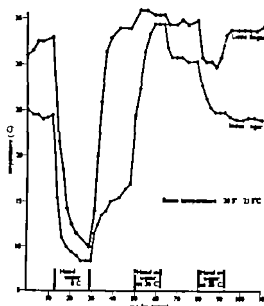


FIG 33 Case E.T., aged 30, (10 4 44). Ri median nerve lesion, complete division show effect of local temperature upon normal a denervated digits.

(ii) *Vasomotor Reflexes*

When one limb is warmed or cooled by immersion in either a hot or cold water bath reflex vasodilatation or vasoconstriction is induced in the other limbs These responses are most easily recorded by studying skin temperature changes in the digits When a limb with an injured nerve is examined in this way it is found that denervated digits respond abnormally In the warm phase the affected digit remains warm throughout the test (Fig. 30) while in the cold phase it will either remain cold throughout or may show a very gradual vasodilatation which is quite unlike the abrupt response shown by the normal digits (Fig. 34). A partially denervated digit (for example, the ring finger in either an ulnar or median nerve lesion) usually shows a normal or almost normal response.

A second type of vasomotor reflex is the brief vasoconstriction which occurs in normal digits in response to such stimuli as a deep breath, a noise or a pin-prick. These responses have to be studied with a plethysmograph as they occur too rapidly to affect skin temperature significantly It has been shown by Bolton, Carmichael and Stürup (1936) and by Doupe (1943a) that they are absent in denervated digits

(iii) *Reactive Hyperaemia*

The hyperaemia which follows a period of circulatory occlusion is independent of the nervous system. If the circulation to a limb with a nerve injury is occluded care being taken to see that the temperature of the limb distal to the site of the occlusion is uniform, the flush which follows the release of the occlusion will spread uniformly over both normal and denervated areas. Furthermore, a digit which exhibits little or no response to reflex vasodilatation will show an appreciable rise in temperature during the period of reactive hyperaemia (Fig. 35) This is in keeping with the hypothesis that reactive hyperaemia represents a response to the metabolic needs of the tissues.

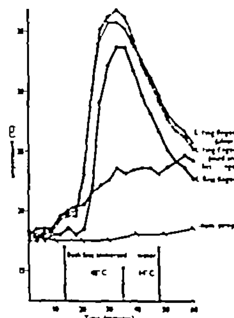


FIG. 34 Case R.H., aged 21 (11 11 41). Left ulnar nerve lesion, complete division showing normal reflex vasodilatation in index finger (normal) ring finger (partly denervated) and gradual tendency to vasodilatation in little finger (completely denervated)

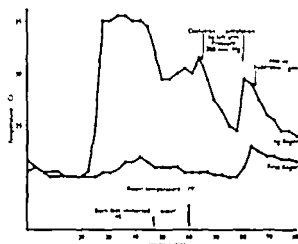


FIG 35 Case Gree, aged 21 (30 4 43) Left median nerve lesion, complete division showing absence of reflex vasodilatation in index finger but rise in temperature during period of reactive hyperaemia

(iv) *Adrenalin and Histamine*

Of humoral substances affecting the peripheral blood vessels the two most important are adrenalin and histamine Since the pioneer work of Elliott (1905) on animals, it has been suggested that after denervation the smooth muscle in the walls of blood vessels becomes hypersensitive to the action of adrenalin Atlas (1938) and Fatherree, Adson and Allen (1940) both demonstrated that blood vessels in denervated digits were sensitive to the vasoconstriction action of adrenalin and their work has been confirmed by others. The most extensive study of the action of adrenalin is that by Doupe (1943c) who concluded that the vessels of denervated digits show a lowered threshold and a prolonged response to the vasoconstrictor action of adrenalin injected intravenously in physiological concentration Responses similar to those obtained by intravenous adrenalin were obtained in response to stimuli with a psychogenic component such as mental effort or intense pain He held that such stimuli liberate adrenalin and that their frequent occurrence in everyday life might be an important factor in reducing the circulation in denervated digits

Histamine is a potent vasodilator of the cutaneous blood vessels. Its action has been carefully studied by Lewis (1927) and others Injected intradermally in minute amounts it produces a triple response local vasodilatation, a spreading flare and the development of a wheal This response is dependent on the integrity of the peripheral nerves After nerve division a normal response is at first obtained in the denervated area but successive tests show that the flare component gradually fades and disappears at about 14 to 21 days. The explanation of this phenomenon will be considered later (p 53) It has been suggested by Tolnick and Beck (1945) that the presence or absence of a histamine flare might be used as a test to differentiate peripheral nerve lesions and hysterical

palsies Nevertheless despite the absence of a classical triple response, histamine still causes a marked vasodilatation in denervated tissues (Fig. 36)

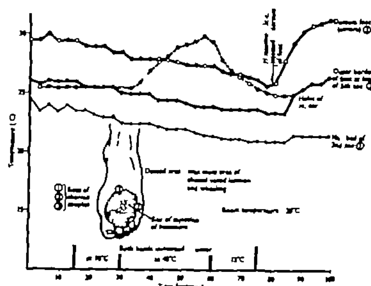


FIG 36. Case L.E.P., aged 27 (3.3 43). Sciatic nerve lesion showing vasodilatation in response to a local injection of histamine in a denervated area which did not respond to reflex vasodilatation.

5 Pathogenesis

A number of hypotheses have been advanced to explain the occurrence of the vasomotor and nutritional disturbances which follow a nerve injury Bowlby (1889) considered the following possibilities

1 That the changes are due to section of the vasomotor nerves and consequent irregularity of the blood supply
2. That they are due to disuse of the paralysed parts.
3 That they are due to irritation of centrifugal fibres.
4 That they are due to the removal of a special (trophic) influence exercised by the nerves on the nutrition of the tissues.

While he admitted that the first three of these factors might contribute to the development of the changes concerned he concluded that it could safely be assumed that nerves do exist which exert a direct trophic influence upon the tissues He was uncertain, however whether this trophic function was subserved by a special group of nerve fibres or whether sensory and motor fibres were responsible for maintaining the nutrition of the tissues which they supplied. His views were generally accepted, and held for many years. Even in the literature on peripheral nerve injuries which followed the war of 1914–18 the theory that the peripheral nerves possessed a trophic function was tacitly accepted

In 1936 however Lewis and Pickering published the results of a study of the vascular and nutritional changes that occur in digits whose nerve supply is divided They studied not only cases of peripheral nerve injury but also the effects of disuse, pure motor paralysis and sympathectomy and were led to the

conclusion that "these changes may all be explained by disuse defects in blood flow and sensory loss and it is unnecessary to assume in explanation any trophic influence of the nervous system" Their investigations were limited to clinical observations and simple experiments and their deductions and arguments were sound and well presented Nevertheless their views do not seem to have met with general acceptance as the adjective trophic is still almost universally used to describe the disturbances which are the subject of this chapter It is therefore worth while to reconsider the problem of pathogenesis in the light of the findings recorded above

The following factors must be considered

(i) *Vasomotor Paralysis*

The peripheral nerves contain vasomotor fibres of autonomic origin These are distributed as direct branches to the larger arteries and as terminal branches to the blood vessels of the skin and subcutaneous tissue over an area similar to that which is normally assigned to the nerve as its territory of sensory distribution (Woollard and Phillips 1932) There is good evidence that as in the case of sensory fibres, vasomotor fibres overlap considerably from one nerve territory into that of adjacent nerves. The principal physiological function of these vasomotor fibres is vasoconstriction and under normal environmental conditions they keep the peripheral blood vessels in a state of moderate constriction Autonomic vasodilator fibres may also exist but if so their physiological importance is much less than that of the vasoconstrictor fibres (Richards, 1946b)

When a nerve is injured these vasomotor fibres are damaged along with motor and sensory fibres. For practical purposes it can be assumed that damage to a fibre means interruption of conduction in that fibre and this will be expressed clinically as vasoconstrictor paralysis. The cutaneous vessels in the territory of the injured nerve dilate and the skin appears hot and flushed The initial warm phase is thus readily explained on the basis of vasomotor paralysis. The completeness of this vasomotor paralysis is shown by the observation of Lathe and Cleghorn (1945) that even in cases of oligaemic shock a leg paralysed as a result of nerve injury remained warm and showed dilated veins while the other extremities were cold and their veins constricted

It is more difficult to explain the later vasomotor and nutritional changes on a similar basis. Except as regards the area affected there is little difference between the appearance of a recently sympathectomized hand and the hand in median nerve palsy which is still in the warm phase After three months however there are striking differences between the two conditions The sympathectomized extremity although not so warm as it was in the immediate post operative period, does not show the extreme coldness atrophic skin, digital atrophy and nail changes which are almost always present in the case of say median nerve palsy

Several attempts have been made to explain the vascular phenomena of the cold phase on the basis of vasomotor paralysis The factors responsible for the recovery of tone in denervated peripheral blood vessels are not yet completely understood It is known that this develops gradually and is complete at about three weeks after denervation a time interval which coincides with the onset of the cold phase. When they have recovered some degree of control the blood vessels will respond to changes in local temperature (Lewis and Landis 1930) Thus in a cold environment cutaneous blood vessels in denervated areas will tend to be constricted

The other important factors which control the calibre of denervated blood vessels are substances circulating in the blood stream and present in the tissues, the most important of which is adrenalin Grant (1935) showed that, in the denervated rabbit s ear the return of vascular tone was due to an increased responsiveness of the vessels to various stimuli including an adrenalin-like substance circulating in the blood White Okelberry and Whitelaw (1936) confirmed this observation and stated that it was applicable to denervated vessels in the limbs of the monkey and of man They also believed that the sensitivity of such vessels was greater after post ganglionic denervation than after section of the pre ganglionic pathway and that the greatest sensitivity occurred at about 21 days after section of the post-ganglionic nerve fibres. Yet although the phenomenon of adrenalin sensitivity' has been considered to be a significant factor in the return of vascular tone following sympathectomy in man recent work suggests that it is relatively unimportant (White, 1949)

A peripheral nerve injury causes post ganglionic denervation and again the time interval corresponds to that which elapses before the onset of the cold phase Atlas (1938 1941) sought to explain the late vascular and nutritional changes on this basis He showed that the vessels in fingers denervated by an injury to the median nerve were sensitive to adrenalin and that this response was not abolished by subsequent pre-ganglionic sympathectomy He concluded that such sensitisation to vasoconstricting influences could be the aetiology of vasomotor and nutritional changes in denervated tissues This aspect of the problem was reinvestigated by Doupe (1943c) who stated that the blood vessels in denervated digits exhibit a lowered threshold and a prolonged response to adrenalin and calculated that adrenalin can be liberated in the body in amounts which would almost certainly be sufficient to initiate and maintain vasoconstriction in a denervated digit.

Even if the actions of local cold and of circulating adrenalin upon the vessels be accepted as an adequate explanation for the coldness of denervated tissues, a further cause has to be sought for the other nutritional changes since both these factors are operative in a sympathectomized extremity which, as already mentioned does not show atrophic skin digital atrophy nail changes, etc.

A sympathectomized extremity and a limb with an injured peripheral nerve differ in one important respect. In the former assuming the sympathectomy to be complete there is complete denervation of the vessels in the extremity in the latter there is a localized area of denervation in a limb with an otherwise intact nerve supply The blood vessels in the normally innervated portion of the limb continue to respond to the usual vasomotor influences acting through the autonomic nervous system As the greater part of the limb cools and warms in response to these influences, a relatively small denervated area is bound to respond also that is to say if the rest of the limb is warm as a result of inhibition of normal autonomic vasoconstrictor tone, the denervated area also tends to become warm This is shown by the gradual increase in temperature observed in denervated digits in response to reflex vasodilatation (p 47 Fig. 34) Conversely when the normally innervated part of the limb is cool or cold as is frequently the case in the environmental temperatures which prevail in Britain the denervated area remains cold. The importance of this factor is also seen in the fact that a completely denervated extremity such as the hand after a complete tear of the brachial plexus or the foot after a complete sciatic nerve lesion shows a greater tendency to remain warm than do the small areas of denervation produced by median or ulnar palsy

A second difference which may be present between a sympathectomized area and a denervated area depends upon the type of the sympathectomy pre-ganglionic or post ganglionic, which has taken place in the latter degeneration of the post-ganglionic neurons will have occurred At one time it was thought that the degeneration of these fibres made the denervated vessels more sensitive to adrenalin (see p 47) and although this has now been disproved evidence has been put forward by Doupe (1943a) that after post ganglionic section the peripheral vessels are more sensitive to the vasoconstrictor action of local cold

If vascular and nutritional changes were due to a vasomotor factor only it would be expected that their incidence would be greatest after injury to those nerves which contain the highest proportion of vasomotor fibres. Up to a point this is true the disturbances are more frequent in cases of injury to the median and medial popliteal than after injuries to the radial or lateral popliteal nerves But when the results for the median and ulnar nerve are compared (p 37) it is found that there is little difference between them which suggests that factors other than vasomotor paralysis must be operative.

(ii) *Sudomotor Paralysis*

The distribution of autonomic sudomotor fibres is similar to that of vaso-constrictor fibres Injury to these fibres as they run in a mixed peripheral nerve results in anidrosis in the autonomous zone of the divided nerve (Fig. 20 p 34) The loss of sweat secretion may contribute in some degree to the atrophy of the skin which occurs after nerve injury but it cannot be an important factor as anidrosis is also present in sympathectomized extremities which do not show any gross atrophy of the skin Furthermore, severe nutritional changes are often observed in incomplete nerve injuries in which hyperidrosis is present

(iii) *Disuse*

The effect of disuse upon the circulation and nutrition of paralysed parts is considerable. An hysterical paralysis produces a hand or foot which is cyanosed cold and slightly swollen Hurst (1920) has described gross nutritional changes including digital atrophy nail changes and even indolent ulceration in cases of hysterical palsy which were cured by psychotherapy alone A finger which is immobilized because of injury to its tendons may develop changes similar to those seen in digits in cases of nerve injury even though sensibility is unaffected and vasomotor activity is normal Similarly in cases of hemiplegia due to brain injury or a cerebro-vascular accident the hand on the paralysed side will show vascular and nutritional changes The former are somewhat variable both vasodilatation and vasoconstriction having been recorded, but the latter are similar to although usually less severe than, those seen in cases of nerve injury In long-standing cases of poliomyelitis the paralysed limbs show a marked tendency to coldness, cyanosis and chilblains. Some of this disturbance may be due to damage to the cells in the lateral horn of the spinal grey matter but it is generally accepted that disuse plays an important role in these circulatory changes.

Disuse leads to a reduction in the metabolism of the paralysed part Freeman (1935) has shown that the blood supply to a sympathectomized hand varies in response to the metabolic needs of the tissues, and it may be assumed that this will apply also to denervated tissues. An increase in blood flow in denervated areas in response to local metabolic demands is easily demonstrated in two conditions, infection and reactive hyperaemia in both, as already described (pp 45 46) a considerable increase in skin temperature can be observed

If disuse is an important factor in the pathogenesis of vascular and nutritional changes, then the incidence and severity of these changes ought to be greatest in those cases in which the nerve injury causes the greatest loss of function A study of the results recorded above suggests that this is substantially true. The highest incidence and most severe changes are observed in combined median and ulnar palsies which produce an almost useless hand. The degree of functional disability which results from ulnar or median palsy is about the same and this is reflected in a similar incidence of vascular and nutritional disturbances when the results for these nerves are compared (pp. 26 37 38) A high median lesion produces more serious disability than a low one and as has been shown on pp. 38 and



FIG. 37 Left median nerve lesion (lesion clinically complete 3 years after injury) showing minimal skin changes and digital atrophy Note atrophied thenar eminence.

39 the incidence of changes is greater in the former On the other hand, the difference in disability caused by a high and by a low ulnar lesion is slight, though if anything a low ulnar lesion produces the more severe disability owing to the increased contracture of the little finger from the action of the flexor profundus. Fig. 28 (p. 40) and Table 9 (p 39) show that the incidence of vascular and nutritional changes is approximately the same for high and low ulnar lesions.

There is no doubt also that, given two patients with similar lesions, vascular and nutritional disturbances will be more severe in the one who makes less effort to use his injured limb (cf Figs. 15 (p. 29) and 37). The effects of disuse are also seen in that digital atrophy and nail changes are often observed in all

the digits of a hand although only one of the main nerves has been injured This is especially true in those cases where a fracture complicates the nerve lesion and adds to the resulting disability

(iv) *Loss of Sensibility*

The effects of the loss of sensibility which follows a nerve injury are complex First the insensitive area is liable to be injured without the patient being aware of it, and this is the most important cause of ulcers blisters and other similar lesions. Similarly the insensitive area being thermanaesthetic, the patient has no subjective appreciation of its coldness and takes no steps to overcome this There is also some evidence that insensitive tissues are unduly vulnerable to trauma In an instance known to the writer of two feet immersed in the same hot bath only the insensitive one was scalded Perhaps an explanation for this is to be found in the observation of Doupe (1943a) that when immersed in a hot (49 C.) bath the temperature of a denervated digit (47° C) rose above that of a normally innervated control digit (43° C) Loss of sensibility however cannot be the most important factor in the development of the majority of the nutritional changes because these are also observed in incomplete nerve lesions in which some sensibility is retained in the affected part

Secondly loss of sensibility means that the affected area has lost its afferent nerve supply Lewis (1927 1936 1942) has shown that nerve fibres belonging to the posterior root system are responsible for a local reaction (the triple response) which occurs in human skin in response to minor mechanical chemical or thermal trauma, and for a similar reaction which follows the intra dermal injection of histamine (p 47) According to Lewis, the flare component of this triple response is due to an arteriolar dilatation which is effected by an axon reflex through pathways in the cutaneous nerve network. After interruption of a peripheral nerve the pathways for this axon reflex remain intact until such time as the nerve fibres distal to the lesion degenerate Thus during the fourteenth to twenty first days after nerve division a fading flare can be obtained whereas later this local vasodilator reaction is lost. Doupe (1943b) has questioned Lewis s hypothesis regarding the mechanism of axonal vasodilatation but for the purposes of this discussion it is immaterial whether Lewis s view about axonal vasodilatation or his conception of the so-called nocifensor nervous system is accepted All that is necessary is the knowledge that in normal skin a local vasodilator reaction occurs in response to all forms of minor trauma and that this reaction is dependent upon the integrity of fibres in the posterior root system these facts are not disputed The importance of this reaction in maintaining the temperature and nutrition of normal skin must be considerable and its disappearance must make denervated tissues more vulnerable to noxious influences in their environment.

The importance of an intact sensory supply is further illustrated by the fact that in some imcomplete lesions (traumatic ulnar neuritis is a good example) and during recovery from complete lesions a stage is present in which autonomic innervation is adequate as shown by normal responses to reflex vasodilatation and vasoconstriction and good sweating, yet there is still subjective and objective coldness of the affected part normal warmth does not return until a high degree of sensory recovery is attained

(v) *Reduced Circulation*

A poor peripheral circulation can be responsible for marked nutritional changes in the skin and subcutaneous tissue Such changes are prominent in cases

of peripheral vascular disease and the most severe example of digital atrophy which the writer has seen was in the great toe of a patient with thrombo-angitis obliterans. It has been suggested that the vascular and nutritional changes in cases of nerve injury are due to associated injury to the blood vessels "these symptoms occur only in cases where there is an arterial lesion in addition to the wound of the nerve" (Athanassio-Benisty 1918) That this is not so is clear from the fact that in none of the cases under consideration was there injury to a major blood vessel There is no doubt, however that the most severe nutritional disturbances are seen only in these cases in which there is also an arterial wound for example, digital gangrene has not been seen except in cases complicated by a vascular injury This aspect will be discussed further in the chapter on neurovascular injuries (Chapter V p. 186)

It is clear from the evidence already presented that the circulation in denervated areas is markedly reduced under normal environmental conditions and although it has been shown that the circulation can increase in response to increased local metabolic needs or with generalized vasodilatation the persistent tendency to a reduced circulation must play a part in the development of nutritional changes.

The possibility that organic changes may be present in the blood vessels in cases of long standing peripheral nerve injury has been raised on several occasions. Stopford (1918) reported intimal changes in the arteries of the foot in a case of sciatic nerve palsy but from the description of his case it appears probable that the femoral artery was also injured. Philippides (1942) and Schulenburg (1949) have also mentioned organic changes in the peripheral vessels in cases of nerve injury but have not presented histological evidence in support of their statements Blackwood (1944b) made a careful examination of the blood vessels in one of the cases in the present series in which a leg was amputated 25 years after a sciatic nerve injury which had shown no sign of recovery He found no changes which could be attributed to the nerve lesion.

(vi) *Nerve Irritation*

At one time the view was widely held that vascular and nutritional disturbances after nerve injury could be due to irritation of nerve fibres. It was originally advanced by Weir Mitchell and was accepted by such notable neurologists as Charcot and Foerster It was argued in favor of this hypothesis that such disturbances were more frequent in cases of incomplete division of the nerve and that they were seen in their most pronounced form in cases of causalgia in which the pain was also attributed to nerve irritation and in which the lesion is almost always incomplete Even in 1889 however Bowlby stated that "in by far the larger number of cases which I have examined and which have shown trophic lesions more or less marked, the section has been complete and there has been no reason whatever to suspect any neuritis or neuralgia" His view is fully borne out by the analysis of the incidence of vascular and nutritional disturbances in the present series of cases. Causalgia is discussed elsewhere in this Report, but it may be mentioned here that the writer is of the opinion that as severe vascular and nutritional disturbances can be seen in cases without pain as are seen in the most severe causalgia and conversely that true causalgic pain can be present with minimal vascular and nutritional changes

The idea that an injury which did not completely interrupt a peripheral nerve might result in irritation of fibres within the injured nerve has for long been accepted by surgeons and neurologists. The precise nature of this irritation has

never been fully explained certainly it is unlikely to be due to scarring either in or around the nerve because in many instances grossly scarred nerves are found at operation in cases where none of the symptoms or signs attributed to nerve irritation has been present

It is believed that satisfactory explanations for most of the vascular and nutritional disturbances which follow nerve injury have been offered above. These hypotheses seek to explain all the observed phenomena as either primary or secondary consequences of the paralysis of nerve fibres and it is therefore hardly necessary to consider nerve irritation as a factor

Two disturbances which are occasionally observed remain for consideration herpetic eruptions and the persistent vasodilatation which is seen in some incomplete nerve lesions. Herpetic eruptions are not common after nerve injury (p 33) but when they do occur they are usually associated with excessive sweating and the eruption is not always confined to the territory of the injured nerve although it is frequently more obvious there because of the atrophy of the skin Doupe and Cullen (1943) have suggested that the vesicles are a variety of cheiropompholyx and this appears a reasonable explanation It is inevitable that a comparison between these eruptions and that of herpes zoster should be made, particularly in view of the hypothesis of Lewis and Marvin (1927) that the results of the latter are due to stimulation of posterior root fibres but the fact that the specific virus can be obtained from the vesicles in cases of herpes zoster makes it improbable that there is any connexion between the two conditions

Occasionally a patient with an incomplete nerve lesion is encountered in whom the affected part remains persistently warm. Two possible explanations for this may be offered first an incomplete lesion may interrupt only a proportion of autonomic vasomotor fibres, and so result only in a disturbance of normal vasoconstrictor tone, the effect of which will be a partial peripheral vasodilatation secondly it has been shown experimentally by Granit, Leksell and Skoglund (1944) that injury to a nerve may produce an artificial *synapse at the point of injury* It has been suggested that if this occurs in incomplete nerve injuries in man then the impulses which are constantly passing along autonomic fibres may in the region of the artificial synapse affect other fibres It is well known that stimulation of posterior root fibres will cause cutaneous vasodilatation (the phenomenon of antidromic vasodilatation) and it may be that such a mechanism could account for peripheral vasodilatation in cases of nerve injury This mechanism provides a more satisfactory physiological explanation for the phenomena attributed to nerve irritation than any previously offered

(vii) *Summary*

This discussion on pathogenesis may be summarized as follows

The warm phase which immediately follows division of a peripheral nerve is due to a vasoconstrictor paralysis. The reasons for the gradual transition to the later cold phase are not completely understood but it is known that at approximately the same time as the transition takes place two significant events occur

(1) The denervated blood vessels regain a certain amount of tone and may become sensitive to the vasoconstricting action of adrenalin

(2) The local vasodilator response to trauma is lost.

The persistent coldness of denervated areas is attributed to the local vasoconstrictor action of low temperature upon denervated blood vessels to the

action of circulating adrenalin to disuse to loss of sensibility and to the influence of the vasomotor state of adjacent normally innervated tissues. Atrophy of the skin and subcutaneous tissues and changes in the nails are due to disuse and a persistently reduced circulation Ulcers blisters and similar lesions are almost invariably the result of unappreciated trauma and are accompanied by an inflammatory reaction Both in complete and in incomplete lesions most of the vascular and nutritional disturbances can be explained as primary or secondary effects of paralysis Nerve irritation is seldom, if ever an important factor and if it occurs the mechanism is probably that of interaction of nerve fibres at the site of injury

II

PART 1 LESIONS IN CONTINUITY

by R B ZACHARY and R ROAF

THE term lesion in continuity is used to denote those nerve injuries in which the continuity of the nerve is preserved Injuries which give rise to predominantly irritative manifestations are considered fully in Chapter IV but incidental reference will be made to them here. Although lesion in continuity is used in contradistinction to division these mutually exclusive titles cannot always be used as first terms of reference in diagnosis, since identical clinical pictures may be presented by the two conditions, and it may be impossible to apply them accurately until the nerve is seen at operation.

The foundation for the precise diagnosis of nerve injuries must be first the delineation of the various clinical syndromes and then the correlation of these syndromes with the gross and microscopical appearances

1 Clinical Syndromes

A DESCRIPTION

In this discussion of nerve injuries the term paralysis is used in its wide sense to include loss of sensory and autonomic as well as motor function Vasomotor paralysis in the sensory distribution of the nerve is described in Chapter 1 and will receive no further comment here. Sudomotor paralysis usually but not invariably runs parallel with sensory loss and will be disregarded in the main categories of classification unless there is some deviation from this general rule

Either motor or sensory paralysis may be transient with no signs of Wallerian degeneration Transient motor palsies do not present the reaction of degeneration (R.D) typical of denervated muscle (see Chapter VI) and stimulation of the nerve trunk distal to the site of injury produces contraction of the paralysed muscles. However care must be exercised in interpreting the electrical reactions of the muscle during the first two or three weeks after injury firstly because the typical reaction may not be fully developed at this stage, and secondly because a normal or abnormal reaction may be obscured by oedema of the injured limb If R.D is present three weeks after injury a degenerative nerve lesion is present Sensory loss is generally incomplete in transient paralysis and frequently disappears altogether within the first month

During the first two to three weeks, therefore, little progress can be made in coming to a precise diagnosis in many cases, and for this reason the discussion will be confined to the clinical and pathological picture of established paralysis that is to say the state of affairs which exists three weeks or more after injury If there is incomplete or no sensory loss and no R.D in the paralysed muscles at this time the paralysis is of the transient non-degenerative type. If on the other hand, complete sensory loss persists and R.D is present the lesion is of the degenerative type

Degenerative paralysis may be complete or incomplete, implying in the one case complete loss of sensibility and motor power and in the other sparing of some function of the nerve. Frequently some degree of both motor power and sensibility is retained, but sometimes one function alone is predominantly preserved the motor loss may be out of all proportion to the sensory or the

action of circulating adrenalin, to disuse, to loss of sensibility and to the influence of the vasomotor state of adjacent normally innervated tissues. Atrophy of the skin and subcutaneous tissues and changes in the nails are due to disuse and a persistently reduced circulation Ulcers, blisters and similar lesions are almost invariably the result of unappreciated trauma and are accompanied by an inflammatory reaction. Both in complete and in incomplete lesions most of the vascular and nutritional disturbances can be explained as primary or secondary effects of paralysis Nerve irritation is seldom if ever an important factor and if it occurs, the mechanism is probably that of interaction of nerve fibres at the site of injury

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A DESCRIPTION

In this discussion of nerve injuries the term paralysis is used in its wide sense to include loss of sensory and autonomic as well as motor function Vasomotor paralysis in the sensory distribution of the nerve is described in Chapter I and will receive no further comment here Sudomotor paralysis usually, but not invariably runs parallel with sensory loss and will be disregarded in the main categories of classification unless there is some deviation from this general rule

Either motor or sensory paralysis may be transient with no signs of Wallerian degeneration. Transient motor palsies do not present the reaction of degeneration (R.D) typical of denervated muscle (see Chapter VI) and stimulation of the nerve trunk distal to the site of injury produces contraction of the paralysed muscles. However care must be exercised in interpreting the electrical reactions of the muscle during the first two or three weeks after injury firstly because the typical reaction may not be fully developed at this stage and secondly because a normal or abnormal reaction may be obscured by oedema of the injured limb If R.D is present three weeks after injury a degenerative nerve lesion is present Sensory loss is generally incomplete in transient paralysis and frequently disappears altogether within the first month

During the first two to three weeks therefore, little progress can be made in coming to a precise diagnosis in many cases and for this reason the discussion will be confined to the clinical and pathological picture of established paralysis that is to say the state of affairs which exists three weeks or more after injury If there is incomplete or no sensory loss and no R.D in the paralysed muscles at this time the paralysis is of the transient, non-degenerative type If on the other hand, complete sensory loss persists and R.D is present the lesion is of the degenerative type.

Degenerative paralysis may be complete or incomplete implying in the one case complete loss of sensibility and motor power and in the other sparing of some function of the nerve. Frequently some degree of both motor power and sensibility is retained, but sometimes one function alone is predominantly preserved the motor loss may be out of all proportion to the sensory or the

sensory loss may be disproportionately severe The demonstration of partial function in a nerve may be an indication of recovery particularly when there is some motor power but no sensibility However the term *sparing* of a function is here used in a wide sense to include such cases.

The clinical syndromes may be summarized as follows

Non-degenerative paralysis — No R D three weeks after injury transient palsy

Degenerative paralysis — R.D present where motor power is affected

(a) *Complete paralysis*

(b) *Incomplete paralysis* — Some sparing of both functions; Predominant sparing of one function — sensory sparing / motor sparing

B INCIDENCE

As a guide to the incidence of these syndromes an analysis has been made of some 1,500 nerve injuries seen at one centre

There was no R.D in 4 per cent of 1,514 nerve injuries, the proportion being highest for the radial nerve (9 5 per cent of 286 cases) and lowest for the median and medial popliteal (1 9 per cent of 366 cases and 1·6 per cent of 64 cases respectively Table 13) Since many transient paralyses recover rapidly it is certain that many of the patients so affected were not sent to a Nerve Injuries Centre and thus the incidence of this type of paralysis is higher than the figures indicate. Table 14 shows that among 1 453 degenerative nerve injuries (with R D) there were 62 per cent in which paralysis was complete, the proportion being highest for the radial nerve (71 per cent of 259 cases) These figures indicate the minimum incidence of complete palsies for some of the incomplete palsies may have been complete at first and subsequently shown some early recovery

TABLE 13

Incidence of non-degenerative and degenerative paralysis

Type of paralysis	Ulnar	Median	Radial	Medial popliteal	Lateral popliteal	Combined sciatic	Total
Non-degenerative	17	7	27	1	5	4	61
Degenerative	488	359	259	63	142	142	1 453
Total	505	366	286	64	147	146	1,514

TABLE 14

Incidence of complete and incomplete paralysis in degenerative nerve injuries

Type of paralysis	Ulnar	Median	Radial	Medial popliteal	Lateral popliteal	Combined sciatic	Total
Complete	303	220	183	36	87	67	896
Incomplete	185	139	76	27	55	75	557
Total	488	359	259	63	142	142	1 453

Table 15 shows the incidence of sparing of one function in cases of incomplete paralysis in 23 per cent of 557 cases there was predominant sparing of one function the highest proportion being in the case of the ulnar (31 per cent of 185 cases) and lowest in the case of the median nerve (9 per cent of 139)

In brief these figures show that about one out of 25 nerve injuries when first seen at the centre was a non-degenerative type of lesion and of the remainder about one third showed incomplete palsy Predominant sparing of one function occurred in about one out of every four incomplete paralyses

TABLE 15

Incidence of sparing of all functions and of one function in incomplete paralysis

Type of sparing	Ulnar	Median	Radial	Medial popliteal	Lateral popliteal	Combined sciatic	Total
All functions	126	124	59	20	40	62	431
One function	59	15	17	7	15	13	126
Total	185	139	76	27	55	75	557

2. Pathology

The distinction between *division* and *lesion in continuity* becomes relevant when the anatomical condition of the exposed nerve is discussed If it is in continuity there are four main types of gross lesion (Fig 38)

1 The nerve may be normal on inspection and palpation
2. There may be a fusiform swelling of the nerve, a *fusiform neuroma* usually rather firmer than normal and sometimes very hard.
3 There may be induration of the nerve without any localized swelling indeed the nerve may be narrower than normal
4 There may be a *lateral neuroma* which is an indication of partial division and the swelling frequently has two humps. If there has been division of only a few bundles there will have been little retraction and the outgrowth of regenerating axons and connective tissue will have filled the gap and produced a single swelling on one side of the nerve. If on the other hand a considerable part of the thickness of the nerve has been divided the two end bulbs do not meet (Fig. 39) In general therefore a double swelling indicates more serious damage than a single one.

The microscopical pathology corresponding to these gross findings must be considered in terms of damage to the nerve fibre. It is in this connexion that the terms neurotmesis, axonotmesis and neurapraxia find their correct application namely to the pathological condition of the nerve fibre, and they should be applied to the nerve trunk only in a distributive sense, e g. neurotmesis of all fibres For convenience each term can be represented by a symbol and a summary of their chief features is as follows (Seddon, 1943)

Neurotmesis (*N*) indicates a complete break in the nerve fibre and the surrounding stroma The epineurium may or may not be intact. There is Wallerian degeneration and no significant re-innervation of the distal stump

Axonotmesis (*A*) implies degeneration of the axon and myelin with preservation of continuity of the stroma. Re innervation of excellent quality is the rule

Neurapraxia (X) denotes loss of conductivity across the lesion without axonal degeneration Recovery is rapid and complete.

Any incomplete lesion in continuity will, of course, contain some conducting fibres. These normal fibres can conveniently be grouped with those of neurapraxia under the general title of 'intact fibres with the symbol (I)

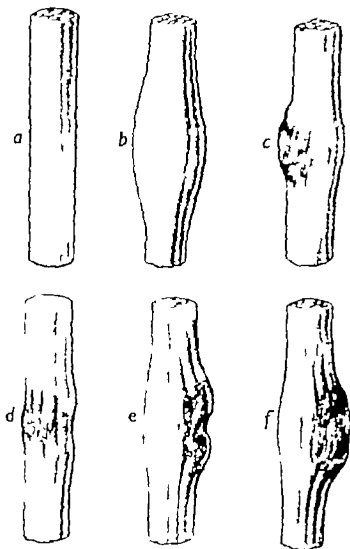


FIG. 38. Diagram showing the usual forms of injury in continuity (*a*) The nerve appears normal at the site of damage. (*b*) Fusiform neuroma which may be firm or soft depending on the extent of intraneural fibrosis. (*c*) A small lateral neuroma with general swelling of the nerve and an obvious break in the epineurium on the left. (*d*) Slight constriction of the nerve with a zone of intraneural fibrosis involving the whole diameter of the nerve. (*e*) Partial division with a separate lateral neuroma and glioma (*f*) Lateral neuroma and glioma in a case of partial division fused to form one lump-like lateral swelling.

Complete division of the nerve clearly corresponds to neurotmesis of all fibres (N)

The four types of lesion in continuity are represented by the following histological pictures

Normal appearance Axonotmesis or intact fibres or a mixture of the two (A I or AI)

Fusiform neuroma The lesion is usually either a mixture of axonotmesis and neurotmesis or a fairly pure axonotmesis a proportion of the fibres may be intact rarely there is complete disruption of all fibres within an intact epineurium (NA A NAI AI or rarely N)

Intraneural fibrosis This group is characterized by widespread neurotmesis which may be localized as after some intraneural injections of noxious substances or diffuse, as in traction lesions and most ischaemic lesions. There may be varying proportions of axonotmesis and occasionally some intact fibres (N sometimes NA and rarely NAI)



FIG 39 Two lateral swellings on the radial nerve, one a neuroma the other a glioma, indicating division of a considerable portion (see Fig. 74 for histological appearances)

Lateral neuroma This is evidence of partial division of the nerve and the microscopic picture is one of partial neurotmesis. The remainder of the nerve usually contains a mixture of intact fibres and those which have suffered axonotmesis, but an important finding has been the presence of a significant amount of neurotmesis in the continuous portion of the nerve (NA or NAI)

It is clear that those fibres which have undergone axonotmesis will recover spontaneously and when this has occurred they will be regarded as intact fibres so that ultimately A or AI will become I and NA and NAI will become NI

3 Correlation of Clinical Syndromes and Pathology

Having described the chief clinical syndromes and the pathological states in nerve injuries, the next task is to establish as far as possible a correlation between the clinical pictures and the various types of lesion in continuity

A NON DEGENERATIVE PARALYSIS

In cases which after an appropriate interval do not show R.D the lesion is likely to be a neurapraxia associated with intact fibres This type of paralysis, frequently termed transient, is almost invariably incomplete Although a complete yet transient and non-degenerative paralysis can be produced for example by local anaesthetics it is rarely the result of injury There is no indication for exploration of the nerve in cases of transient paralysis However *the opportunity to examine the lesion may occur incidentally during the course* of an operation undertaken for another reason as in the following case

W.31 Gun shot wound near the elbow When the patient was examined two hours later there was paralysis of all muscles of ulnar innervation except flexor digitorum profundus. There was complete loss of tactile sensibility in the ulnar zone of distribution, but loss of pain sensibility only at the tip of the little finger The nerve was seen during the débridement of the wound. Its sheath was intact except for one short tear and the underlying bundles were not severed. There was haemorrhage around the nerve. Sensory recovery started on the day following the injury and motor recovery in the interossei began on the twelfth day far too soon to be due to regeneration. In six weeks motor and sensory function was nearly normal. Normal electrical excitability was retained by the paralysed muscles, a proof of the non-degenerative character of the paralysis.

The nerve usually shows little alteration from normal but the epineurium may be ruptured as in the above case, or there may be a little thickening due to post traumatic inflammatory exudate or the extravasation of blood within the sheath A zone of constriction can also produce neurapraxia

B DEGENERATIVE PARALYSIS

(I) *Complete Paralysis*

Complete paralysis may be a manifestation of complete division or of any of the four types of lesion in continuity and the interpretation of these four types is greatly simplified by the *completeness of the paralysis and the absence of* intact fibres. The relationship between the clinical picture and the pathology in complete degenerative paralysis is as follows

Syndrome	Gross pathology	Microscopic pathology
Complete degenerative paralysis	Division	N
	Lesion in continuity	
	Normal appearance	A
	Fusiform neuroma	NA, A or N
	Intraneural fibrosis	N or NA
	Lateral neuroma	NA

TABLE 16

Incidence of complete division and of lesion in continuity in complete paralysis

Type of lesion	Ulnar	Median	Radial	Medial popliteal	Lateral popliteal	Combined sciatic	Total
Complete division	233	156	100	19	35	29	572
Lesion in continuity	70	64	83	17	52	38	324
Total	303	220	183	36	87	67	896

Some hint of the probable underlying pathology can be obtained by examining the incidence of some of the pathological findings in cases of complete paralysis (Table 16) In 896 complete paralyses a complete division was found in 64 per cent The proportion was highest for the ulnar and median nerves (77 and 71 per cent respectively) and lowest for the sciatic (43 per cent)

Although these figures were accurate for the particular time of examination and were therefore readily comparable with those of other groups of nerve injuries seen after a similar delay they did not record those paralyses which may have been complete at the outset and recovered to some extent before examination. However the lowest estimate of the proportion of complete divisions in complete paralyses can be deduced by assuming that all the incomplete degenerative palsies were complete at first. Table 17 shows that 39 per cent of 1 453 degenerative palsies were due to complete division the proportion gradually decreasing in the following order ulnar 48 per cent median 43 per cent, radial 35 per cent, medial popliteal 32 per cent, lateral popliteal 25 per cent and the sciatic nerve 20 per cent. These figures err in the direction of an under estimate and it seems reasonable to conclude that at the time of injury 50 to 60 per cent of all complete median and ulnar palsies were due to complete division of the nerve and that the proportion was 30 to 50 per cent for the other nerves The longer the interval since injury the more likely is it that a complete paralysis is due to division of the nerve

These figures were of practical importance in formulating indications for exploration and repair of nerves furthermore since certain partial divisions could also be repaired, the incidence of partial as well as complete divisions is worth recording (Table 18) Among 1 453 degenerative nerve injuries 52 per

TABLE 17

Incidence of complete division and of lesion in continuity in degenerative paralysis

Type of lesion	Ulnar	Median	Radial	Medial popliteal	Lateral popliteal	Combined sciatic	Total
Complete division	233	156	100	19	35	29	572
Lesion in continuity	258	203	159	44	107	113	881
Total	491	359	259	63	142	142	1 453

TABLE 18

Incidence of division (complete or partial) and of no division in complete or partial degenerative paralysis

Type of lesion	Ulnar	Median	Radial	Medial popliteal	Lateral popliteal	Combined sciatic	Total
Division	286	213	121	33	56	51	760
No division	205	146	138	30	86	91	693
Total	491	359	259	63	142	142	1 453

cent were due to complete or partial division—58 and 59 per cent for the ulnar and median nerves respectively and 42 and 36 per cent for the radial and sciatic nerves respectively If the analysis was restricted to those palsies which were complete at the time of examination it was found that 80 per cent of complete median or ulnar palsies were due to complete or partial division 52 per cent of sciatic palsies were caused by similar lesions, and the proportions for the other nerves were intermediate (Table 19)

TABLE 19

Incidence of division (complete or partial) and of no division in complete degenerative paralysis

Type of lesion	Ulnar	Median	Radial	Medial popliteal	Lateral popliteal	Combined sciatic	Total
Division	244	171	110	25	44	38	632
No division	59	49	73	11	43	29	264
Total	303	220	183	36	87	67	896

A further guide to the condition of the nerve was obtained by considering the incidence of division or partial division in open and closed injuries (Tables 20 and 21) From the figures in these tables it is clear that, at the time when the patients were first seen in the Nerve Injuries Centre, there was a very high probability of complete or partial division being responsible for complete paralysis in open wounds—almost 90 per cent (88 per cent ± 4) for the median and ulnar nerves, and more than 70 per cent (72 per cent ± 7 5) for the radial and between 75 and 90 per cent for the sciatic nerve and its branches.

TABLE 20

Incidence of division (complete or partial) and of no division in complete paralysis due to open injuries

Type of lesion	Ulnar	Median	Radial	Medial popliteal	Lateral popliteal	Combined sciatic	Total
Division	243	170	101	25	44	38	621
No division	33	21	39	7	5	13	118
Total	276	191	140	32	49	51	739

TABLE 21

Incidence of division (complete or partial) and of no division in complete paralysis due to closed injuries

Type of lesion	Ulnar	Median	Radial	Medial popliteal	Lateral popliteal	Combined sciatic	Total
Division	1	1	9	0	0	0	11
No division	26	28	34	4	38	16	146
Total	27	29	43	4	38	16	157

Among the closed injuries (Table 21) nine out of 43 complete radial palsies (21 per cent) and one out of 27 ulnar palsies were due to complete or partial division Thus it is clear that in complete paralysis due to closed injuries division of a nerve is unlikely except in the case of the radial The case of division of the ulnar nerve was so unusual that a summary of the history is given

E.41 Direct blow on the upper arm by a falling wireless mast fracture of the humerus at the junction of the middle and lower thirds but no break in the skin. Two days later he was found to have signs of ulnar palsy Six months afterwards there was still a complete ulnar paralysis with anomalous innervation of the first dorsal interosseous muscle, and when the nerve was explored it was found to be completely divided.

(ii) *Incomplete Paralysis*

Incomplete paralysis is an indication of a lesion in continuity unless the paralysis is incomplete by virtue of anomalous innervation The anomaly generally concerns one function usually motor and the question will be dealt with later in considering the causes of incomplete paralysis with sparing of one function.

Some correlation is possible between the incomplete degenerative palsies and the several types of lesion in continuity In the later section of this chapter which deals with the indications for operation and repair it will be shown that repair is frequently possible in cases of partial division of the nerve Hence it is important to identify those clinical pictures which are compatible with a partial division and those in which such a diagnosis is unlikely

(*a*) *Partial loss of all functions*

More than three quarters of the cases of incomplete paralysis had some sparing of both motor power and sensibility In the peripheral portion of any mixed nerve there is a gradually increasing segregation of groups of motor and sensory fibres, and thus for some distance (varying from nerve to nerve) proximal to the terminal branching of the nerve trunk the funicular pattern corresponds to the main motor and sensory branches of the nerve (Sunderland 1945) Consequently an injury to one side of the nerve trunk at this level would affect predominantly one group of fibres, for example the motor leaving the other group virtually untouched. More proximally the motor and sensory fibres are intermingled throughout the thickness of the nerve so that an injury to one sector would spare both motor and sensory fibres in the remainder

A further cause of the variability in the clinical picture in this group of cases is that all degrees of damage may be found at all levels. However it is possible to generalize as follows

Incomplete degenerative paralysis

Sparing of all functions

Proximal site of injury	Although the damage may be scattered throughout the nerve the picture is compatible with an injury to one sector and hence with a partial division.
Distal site of injury	Neither of the main funiculi (motor and sensory) can have been divided The extent of the sparing is a guide to the degree of damage and must influence any decision, but, in general a serious partial division is unlikely

Table 22 shows the incidence of partial division in cases of incomplete paralysis with sparing of all functions. Among 431 incomplete degenerative palsies there were 21 per cent of partial divisions, ranging from 15 per cent for the radial to 35 per cent (of 20) for the medial popliteal nerve. When the incidence is considered in relation to the type of wound (Table 23) it is found that 30 per cent of 298 incomplete palsies following open wounds were due to partial division. Among the closed injuries there were only two partial divisions and these were radial nerve injuries.

TABLE 22

Incidence of partial and of no division in incomplete degenerative paralysis with sparing of all functions

Type of lesion	Ulnar	Median	Radial	Medial popliteal	Lateral popliteal	Combined sciatic	Total
Partial division	26	33	9	7	7	10	92
No division	100	91	50	13	33	52	339
Total	126	124	59	20	40	62	431

TABLE 23

Incidence of partial and of no division in incomplete degenerative paralysis with sparing of all functions in open injuries

Type of lesion	Ulnar	Median	Radial	Medial popliteal	Lateral popliteal	Combined sciatic	Total
Partial division	26	33	7	7	7	10	90
No division	52	64	26	11	20	35	208
Total	78	97	33	18	27	45	298

(b) Sparing of one function

Where there is sparing of one function out of all proportion to another the interpretation depends on the site of injury If the site is close to the branching of the nerve and the sparing corresponds to the distribution of a branch, the damage is funicular and may be a partial division. If on the other hand the site of injury is more proximal where the motor and sensory fibres are intermingled in all funiculi the paralysis is probably due to the selective damage to one type of fibre and not to an injury to one sector of the nerve This sort of selective damage is frequently the result of a traction injury but it may be found in other types of trauma. Most commonly it is the fibres of larger calibre (especially the motor and proprioceptive fibres) that suffer more than the others This syndrome of sparing of one function in a proximally situated injury is not usually compatible with the diagnosis of a partial division although there are some exceptions which will be mentioned later

Sensory sparing

Proximal site of injury profound motor paralysis with little or no sensory loss may be due to selective damage to the motor fibres, the injury being a diffuse one through the whole thickness of the nerve Such a picture is not infrequent in paralysis due to traction or sometimes compression of a nerve and is termed *dissociated paralysis*

The following example is typical

L51 Paralysis of the arm following a nasal operation under general anaesthesia. When examined two and a half months after the incident the patient showed weakness of the shoulder and arm muscles and complete paralysis of all muscles supplied by the radial nerve and of the intrinsic muscles of the hand with R.D There was no area of complete loss of sweating or sensibility but there was a patch of slight hypoasthesia on the little finger and ulnar side of the palm.

It is not unusual to find preservation of all forms of sensibility even including the finer grades such as two-point discrimination Sometimes however tactile sensibility is lost and pain retained Rarely all sensibility is lost but sweating is preserved throughout the zone supplied by sensory branches The term dissociated paralysis is applied to all these varieties.

In the case of the lateral popliteal nerve the autonomous zone of sensory distribution may be small and in the radial nerve it may be absent. Sensory overlap of this sort gives rise to a clinical picture similar to that found in dissociated paralysis, but in the case of these two nerves the preservation of sensibility is compatible with a complete paralysis

Distal site of injury sensory sparing is an indication of a lesion on one side of the nerve affecting the motor funiculi the picture is compatible with a partial division. There is, however an important caveat In children the autonomous zone of cutaneous distribution of a nerve is sometimes small especially for pain. Accurate determination of tactile sensibility is often difficult, and reliance has to be placed chiefly on responses to pin prick In several cases of median nerve injury the finding of analgesia confined to the tips of the index and middle fingers led to the wholly erroneous conclusion that the nerve was in continuity and that recovery was occurring. Later when a belated exploration was performed the nerve was found to be completely divided.

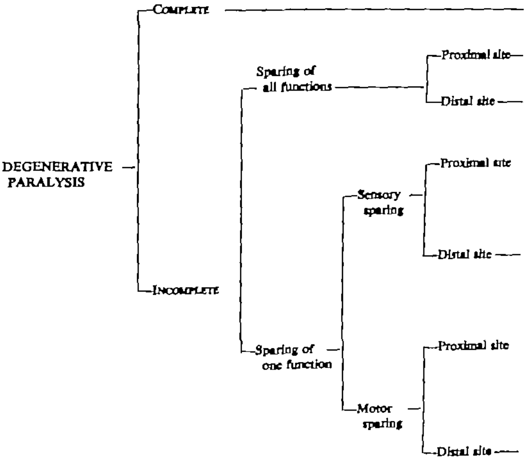
Motor sparing

Proximal site of injury a not infrequent finding in this clinical syndrome is that the motor sparing is due to anomalous innervation and the picture is actually that of complete paralysis, with the possibility of complete or incomplete division of the nerve. These conditions are most commonly encountered in ulnar paralysis where the persistence of activity in the interossei and occasionally in the hypothenar muscles is due to their innervation by the median nerve as in the following case

D 18. Accidental division of the ulnar nerve during an operation for repair of an injured triceps. The section of the nerve was complete and immediate repair was performed. Three weeks later when the patient was seen at a Nerve Injuries Centre, there was paralysis of flexor carpi ulnaris, flexor digitorum profundus to the little finger and complete loss of sweating and sensibility in the ulnar area. All the ulnar intrinsic muscles were acting. Stimulation of the ulnar nerve at the wrist gave a good response in the interossei and the hypothenar muscles, but stimulation at the elbow produced no response. Blocking of the median nerve near the elbow caused complete paralysis of all the intrinsic muscles. In this case an anomalous branch from the median nerve joined the ulnar in the forearm and carried fibres to the intrinsic muscles usually supplied by the ulnar nerve.

Clinical syndromes correlated with

NON DEGENERATIVE PARALYSIS (Transient Palsy Neurapraxia)



gross and microscopical pathology (see p 70)

	Gross pathology	Symbol of microscopic pathology
	Essentially normal appearance	I
	Complete division	N
	Lesion in continuity perhaps partial division	A N NA
	Lesion in continuity perhaps partial division	AI NI, NAI
	Lesion in continuity partial division unlikely	AI
Dissociated paralysis	Lesion in continuity not partial division	AI, NAI
Anomalous innervation Sensory overlap	Complete division	N
	Lesion in continuity perhaps partial division	A, NA
Anomalous innervation Sensory overlap	Complete division, lesion in continuity partial division	N A, NA
Partial lesion	Partial division	NI
	Lesion in continuity	AI, NAI
Dissociated paralysis	Lesion in continuity partial division unlikely	AI NAI
Anomalous innervation	Complete division	N
	Lesion in continuity perhaps partial division	A, NA
Anomalous innervation	Complete division, lesion in continuity partial division	N A, NA
Partial lesion	Partial division	NI
	Lesion in continuity	AI NAI

A similar clinical picture has been seen in nerve injuries associated wi ischaemia, in which the peripheral sensory branches of the nerve have suffere ischaemic damage, as in the following case

O 15 Gun-shot wound of the upper arm. A few days later the patient was found to ha ulnar paralysis with loss of the radial and ulnar pulses. Two and a half months after inju there was active movement of the interossei (far too soon to have been due to regeneratio but ulnar sensory loss persisted and was almost complete. Biopsy of the dorsal cutaneo branch of the ulnar nerve showed collagenization similar to that found in ischaemia.

In some instances, as for example in ulnar neuritis, extensive sensory lo without motor paralysis is not due to anomalous innervation. It must be du either to an *unusual type of selective damage in which the smaller* (sensor fibres are affected most or to a strange anatomical arrangement of the fibres a the elbow in which sensory axons, although in different funiculi, are sti congregated mainly in the sector which has sustained most of the damage. Th interpretation of this syndrome must still be made with some reserve.

Distal site of injury if the lesion is situated close to the main branching o the nerve, the damage is probably confined to one sector of the nerve and th picture is compatible with a partial division.

The incidence of partial division in incomplete degenerative paralysis wit sparing of one function is shown in Table 24 Twenty nine per cent of then 126 palsies were proved to be due to partial division All the partial division followed *open wounds, of which there were 76 thus almost half of the paralyse* of this type following open injuries were caused by partial division of the nerve

TABLE 24

Incidence of partial and of no division in incomplete degenerative paralysis with sparing of one function

Type of lesion	Ulnar	Median	Radial	Medial popliteal	Lateral popliteal	Combined sciatic	Total
Partial division	16	9	2	1	5	3	36
No division	43	6	15	6	10	10	90
Total	59	15	17	7	15	13	126

The correlation between the clinical syndromes and the gross and microscopical pathology may be summarized as on pps. 68, 69

consideration since there is a far greater likelihood of the nerve having been completely or partially divided after an open injury than after a closed one.

A COMPLETE PARALYSIS

(i) *Open Injuries*

In cases of complete paralysis due to open injury it is probable that the nerve has been either wholly or partially divided and if the paralysis is still complete after the wound has healed it is wise to perform an *exploratory operation* unless there is some specific contra indication Even where an intact nerve is found the operation has not been in vain If a good prognosis can be given the patient is reassured and his co-operation is gained in securing an early restoration of function In a greater proportion of cases serious damage to the nerve will be found and surgical repair required In these cases early operation will give a more favourable prospect of recovery

It has been argued that the policy of early exploration will lead to unnecessary resection of some lesions in continuity lesions which would have recovered spontaneously and in a manner far better than after suture. Such a warning is timely at this stage of the discussion and it must be emphasized that the decision to resect a lesion in continuity should be made only after full consideration of all the circumstances. However even if early exploration is performed solely for the purpose of discovering the completely divided nerves, the procedure is still justified in cases of complete paralysis due to open wounds in view of the high incidence of complete division in this group

There are of course certain circumstances in which operation must be delayed for instance, the patient s poor general condition active sepsis elsewhere in the body associated lesions requiring prior attention or impairment of the blood supply to the limb of such a degree that an operation might do harm.

(ii) *Closed Injuries*

After closed injuries it is far less likely that the nerve has been completely divided and hence there can be no general recommendation of early exploration Exploration, which in this group of cases is the exception rather than the rule, is necessary only in the following circumstances

Delay in recovery if the site of the lesion is known (an approximation is seldom difficult) it is possible to calculate the expected date of spontaneous recovery of the most proximal muscles. If for example the point of innervation of the muscles is 100 mm. from the site of injury there should be some recovery in 100 days provided the injury is a pure axonotmesis. There is, however fre quently some delay so it is reasonable to allow an additional 20 to 30 days. Moreover it should be remembered that the point of innervation is seldom at the upper extremity of muscles (Seddon Medawar and Smith, 1943 Sunderland 1946)

If recovery is delayed much beyond this time it is probable that a considerable number of fibres have undergone neurotmesis and the nerve should be explored

Should there be difficulty in estimating the expected time of recovery owing to ignorance of the exact site of the lesion a safe guide is to explore the nerve if there is no recovery after five or six months. After such an interval suture, if found to be necessary can still often produce a useful result and yet there will be some safeguard against unnecessary exploration and resection

The possibility of *persistent compression* complete paralysis complicating a closed fracture is usually due to compression Although the action of the trauma is usually momentary the nerve may sometimes remain compressed by

bone fragments and the fibres which have suffered axonotmesis fail to show the expected recovery Thus, exploration carried out on account of absence of recovery at the expected time may very occasionally reveal not a divided nerve but one compressed by bone, and neurolysis will lead to recovery

In neurovascular injuries pressure from an adjacent aneurysm may prevent recovery in a nerve that is not seriously damaged *The choice of time for opera tion is discussed in Chapter V* Compression of a nerve by scar tissue is frequently put forward as a reason for exploration but there have been very few cases in which such compression could be demonstrated

(a) Traction injuries

The intraneural damage is always extensive but extremely variable in severity In complete palsies due to traction the damage is often serious and may consist of widespread neurotmesis with no hope of spontaneous recovery At the best there will be much intraneural scarring which will impede the progress of regeneration and so prolong the delay before recovery becomes apparent. If exploration is delayed until there has been a reasonable chance of spontaneous re innervation repair of the nerve would be too late to offer much prospect of recovery Consequently if the aim is to repair such lesions one must explore them early or not at all.

The prospect of spontaneous recovery and the feasibility of repair vary for different nerves and so modify the indications for exploration

Barnes (1949) in reviewing cases of degenerative paralysis of the brachial plexus from three centres, showed that recovery was adequate in approximately half of the lesions confined to the upper three nerve roots, C5 6 7 On the other hand recovery was rare in lesions of the lower roots, and when the whole plexus was involved only half of the patients showed any recovery at all and this was restricted to the upper trunk Thus there is an even chance of spontaneous recovery in the upper roots but virtually no hope of it in the lower ones. Repair of traction lesions of the plexus by autogenous grafting was performed on three occasions and, although in no case was recovery satisfactory the possibility that the technique will be improved sufficiently to make it worth while should not be entirely discounted Occasionally exploration of a case of complete brachial plexus paralysis will reveal rupture of the roots, often at such a high level as to preclude repair possession of this information will save a patient many months of useless conservative treatment.

Sciatic palsy

Sciatic palsy accompanying dislocation of the hip is often incomplete, the medial popliteal division being the less seriously damaged Even when complete, the paralysis is seldom permanent and as the degree of recovery is at least as good as that which could be expected *from repair of* an extensive lesion there is no reason for exploration

Paralysis of the lateral popliteal nerve in adduction injuries of the leg is usually complete. Occasionally complete rupture occurs and in such cases repair may be feasible In the usual type of case where the nerve is in continuity there are great difficulties in deciding whether recovery will occur or not. Provided there are facilities for expe terpretation of mu nerve biopsies, reinforced by an intelligent ion of the naked ances of these lesions, exploration may for prognosis s for repair Where such facilities do not little to be gai oring these traction lesions apart from the ga rupture runk.

(b) Injuries due to intraneural injection

Complete palsies have been caused by the accidental intraneural injection of a noxious substance such as one of the sulphonamides (notably sulphapyridine) heparin and pentothal Occasionally the severity of such a lesion is at once apparent on exploration

H 167 Injection of Sodium Pentothal into the median nerve at the elbow Ten months later the nerve was explored at the site of injection it was extremely narrow and above and below there were bulbous swellings. Most of the bundles were completely destroyed and resection and suture were necessary (Fig. 40).

In many cases however there is little obvious abnormality at the site of injection and the advantage of early exploration is less obvious However many of these injuries affect the sciatic nerve and to delay exploration until there is evidence of recovery might waste a year if the nerve needed repair Early exploration of the sciatic nerve is therefore, advisable, with the aid of muscle and nerve biopsy which are often the only guides to the necessity for resection In other cases exploration should be deferred until there has been time for recovery to occur

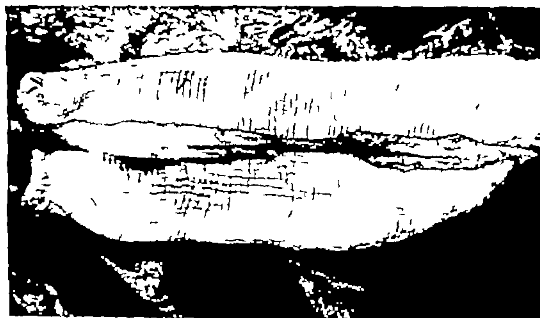


FIG. 40 Extreme narrowing of the median nerve due to an intraneural injection of Sodium Pentothal. The neuroma on the left is rather larger than in other cases of this type of injury

B INCOMPLETE PARALYSIS

Where the paralysis is incomplete the indications for operative intervention are fewer and therefore require even more careful definition At the first examination it is often difficult to be sure whether incomplete paralysis represents the original state of affairs or indicates partial recovery If the latter there may be further recovery or the process may have come to a standstill. Consequently a second examination after an interval of a few weeks will sometimes help in establishing the indications for exploration Although there may be no great change in voluntary power or sensibility during this period the electrical reactions and electromyographic behaviour of the paralysed and weak muscles may indicate that recovery is still in progress (See Chapter VI)

(i) *Open Injuries*

In general exploration is indicated in cases of partial paralysis associated with

open injuries whenever it is likely that the nerve has suffered partial section The various clinical pictures that may be produced by partial division have been described and are summarized as follows

(1) Partial *sparing of motor power and sensibility in a proximal lesion.*

J 49 Wound of the arm which caused weakness but no paralysis of the ulnar intrinsic muscles, and anaesthesia with hypoalgesia in the ulnar sensory zone. Exploration revealed a partial division of the ulnar nerve which was amenable to repair (See Fig. 268, p. 400.)

(2) Motor paralysis but sparing of sensibility in a distal lesion.

G.33. Laceration of the ulnar border of the forearm resulting in complete paralysis of the ulnar intrinsic muscles but considerable sparing of sensibility in the ulnar area. At exploration a partial division of the ulnar nerve was found and the motor portion was repaired.

(3) Motor paralysis but sparing of sensibility in a proximal lesion where the sensory sparing is due to overlap

S 131 A wound of the arm causing complete paralysis of the muscles supplied by the radial nerve no loss of sensibility At exploration the nerve was found to be divided.

(4) Sensory paralysis but sparing of motor power in a distal lesion

K.32. Laceration of the wrist causing extensive sensory loss in the median area but preservation of some power in the thenar muscles. At exploration the median nerve was found to have a serious partial division which was repaired (Fig. 41).

(5) Sensory loss with sparing of *motor power in a proximal lesion*, where the motor sparing is due to anomalous innervation.



Fig. 41 The lateral neuroma and glioma in a case where about two thirds of the median nerve had been divided at the wrist. Loss of sensibility in the hand was almost complete but the thenar muscles were acting well.

A 42. Wound at the elbow causing ulnar sensory loss but the ulnar intrinsic muscles were found to be active. Exploration revealed complete division of the ulnar nerve at the elbow with anomalous innervation of the interosseous and hypothenar muscles.

Naturally the severity of the paralysis must be taken into account, but if it is at all serious there is a strong case for early exploration.

Anomalous innervation is investigated in the first place by percutaneous stimulation of the injured and adjacent nerves. Two types of anomaly can be demonstrated in this way: branches may enter the trunk of the injured nerve below the level of the lesion or anomalous fibres may travel the entire length of the adjacent nerve before being distributed at the periphery.

Further and even more convincing proof of anomalous innervation is provided by a nerve block (Highet, 1942a). The injection of a local anaesthetic (2 per cent procaine) around one of the nerves of the limb or nerve trunks is often insufficient to produce complete paralysis. The epineurium is thick and, especially around the elbow, *there may be other fascial layers interposed* between the nerve and the anaesthetic solution. Consequently the injection must usually be made into the nerve in order to ensure a satisfactory effect.

The paralysis resulting from such an intraneural injection usually lasts long enough to allow a thorough neurological examination of the limb including a sweating test. Complete recovery from the anaesthetic may not occur for several hours and thus, if more than one site has to be blocked, it is wise to postpone the second procedure until the following day, unless it is desired to study the effect of the simultaneous blocking of two nerves.

Although anaesthetizing the injured nerve above or below the site of injury sometimes gives the information required, blocking an adjacent nerve or nerves is often more valuable. For example, if there is preservation of activity in the thenar muscles in an otherwise complete median palsy there may be an incomplete paralysis or anomalous innervation. If there is no change on blocking the median nerve it is possible that the block has been unsatisfactory. On the other hand, if the ulnar nerve is blocked, causing paralysis of the interossei and loss of sensibility in the ulnar area, the block is *known* to be complete: the persistance of activity in the thenar muscles then proves that they are supplied by the median nerve whereas their paralysis proves that they are supplied by the ulnar.

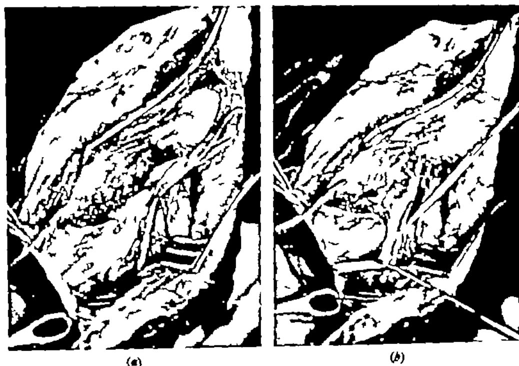
(ii) *Closed Injuries*

The five clinical pictures described above as being compatible with partial division of a nerve are also valid for closed injuries, but there is less justification for exploration since the incidence of partial division is far less after closed than after open wounds.

As in the case of complete paralysis due to closed injury, delay in recovery and the possibility of persistent compression are indications for exploration. Two additional indications are pain and deterioration of function. Here it suffices to say that there are some lesions in continuity in which pain is relieved by freeing the nerve from external pressure or scar and placing it in a better bed. Deterioration of function is rare after partial recovery; it is, however, not infrequent as a late sequel to an injury (either open or closed) which is in the vicinity of a nerve even where there has been no initial paralysis. The most common example is delayed ulnar neuritis at the elbow, but examples of median neuritis at the wrist have also been met. It sometimes follows the resumption of joint movements when a nerve is adherent at the site of a fracture, as in the following example:

S 174 Fracture of the humerus due to a gun-shot wound, with no nerve injury Five months later the fracture was well united and elbow movements were started. Three weeks later there was a gradual onset of paraesthesiae on the dorsum of the hand followed by numbness. The patient was found to have loss of pain and tactile sensibility in the superficial radial area, and there was slight radial motor paresis. At operation the radial nerve was found to be closely adherent to a bony projection at the fracture site (Fig. 42.)

If an operation is required for associated lesions, such as bone, joint or tendon injuries, it is a convenient occasion to observe the state of the nerve.



(a) (b)

FIG 42. (a) A dissection of the radial nerve in a case of mal-union of the humerus. The symptoms of radial nerve involvement appeared when movements of the elbow were permitted. (b) The nerve has been dissected off the bony prominence.

5 Operative Procedures

(i) *Anaesthesia*

The choice of anaesthetic is influenced by the preferences of the patient and surgeon the general condition of the patient and the availability of good general anaesthesia The advantage of local anaesthesia is that it permits the testing of sensibility when the nerve trunk is stimulated electrically distal to the lesion. In order that this test should be of value it is necessary that the patient should be co-operative and neither unduly apprehensive nor drowsy as a result of premedication In addition, it should be recalled that misleading positive responses are sometimes obtained even when the nerve is completely or almost completely severed, a point to which further reference will be made later (p 79) Unless there is some specific contra indication general anaesthesia is preferable With increasing experience British surgeons abandoned local anaesthesia and felt confident that they could safely dispense with whatever information sensory stimulation might provide in the investigation of the doubtful lesion in continuity

(ii) *Tourniquet*

A difficult dissection can be most easily and safely performed in a bloodless field. If a tourniquet is used it should be of the pneumatic type, and, provided the cuff is applied carefully and the pressure maintained about 70 mm. above the systolic pressure it can be employed for between two and two and a half hours

without danger It should be released after the dissection is complete, and certainly before nerve suture is performed for otherwise there is risk of a haematoma forming at the site of suture.

(iii) *Isolation of the Lesion*

Wherever possible it is wise first to expose the nerve trunk in normal surroundings above and below the site of injury and to stimulate the trunk above and below the lesion with a weak faradic current *before* dissecting the lesion itself from the surrounding scar It will usually be apparent whether the nerve is in continuity though occasionally dense extra neural tissue may make even this elementary observation impossible If the nerve has been completely divided or if there is only a thin strand of fibrous tissue between the neuroma and glioma repair is indicated A centrally situated connecting band is nearly always composed of scar tissue, whereas a lateral one may contain intact fibres. If the lesion is in continuity one of the following four conditions may be met normal on inspection and palpation fusiform neuroma, intraneural fibrosis, and lateral neuroma.

Normal appearance The underlying pathology is axonotmesis with or without intact fibres Spontaneous recovery is to be expected and interference should be limited to ensuring that the nerve lies in a bed free from scar

Fusiform neuroma The extent of damage is assessed in the following ways

Inspection The size of the neuroma is some indication of the degree of damage, but the correspondence is not exact and other factors must be taken into consideration A large neuroma usually indicates extensive damage but a small one is not necessarily favourable. A neuroma of a diameter up to twice that of the normal nerve is compatible with either extensive neurotmesis or good spontaneous recovery

Palpation. The consistency of the swelling is a fair guide to the amount of scar tissue it contains and taken in conjunction with its size, provides a reasonably accurate guide to the severity of the injury Thus a small soft neuroma usually indicates comparatively little damage, a large hard one extensive damage.

W 67 Gun-shot wound of the arm causing ulnar paralysis At exploration a large firm neuroma was found (Fig. 43) The lesion was not resected, and recovery was very poor



FIG 43 A large firm fusiform neuroma in the ulnar nerve at the elbow No signs of recovery after 8 months.

Stimulation. If nerve fibres are intact and conducting, electrical stimulation will initiate nerve impulses which may produce the appropriate sensory or motor response A positive motor response shows that some fibres are intact and conducting, but a positive response in one or two muscles does not necessarily mean that the majority of motor fibres are intact, and the ultimate spontaneous recovery might be poor Absence of motor response when stimulating distal to the lesion is proof of Wallerian degeneration but there is no indication as to whether it is due to neurotmesis or axonotmesis. If however under local anaesthesia, there is no sensory response to stimulation just distal to the lesion most of the fibres have undergone neurotmesis. A positive sensory response may be due to sparing or to recovery but it may also occur in the following circumstances

(1) A few fibres may have bridged the gap but they may not be sufficient to lead to useful recovery

(2) Too strong a current may have been used with the result that the current has spread across a non functioning portion to the normal trunk above. A current strong enough to produce a weak contraction when applied to an adjacent muscle is usually sufficiently strong to give a response in sensory fibres.

(3) Antidromic impulses appear to be set up in some instances which spread by way of peripheral anastomoses

Thus stimulation of the nerve can give useful information provided the limitations of the method are born in mind.

In the case of the fusiform neuroma the information gained by inspection, palpation and stimulation together with that obtained from clinical examination is often sufficient to enable a decision to be made, and this is usually to leave the nerve alone and to close the wound Sometimes however the information is inadequate there is no certain evidence that regeneration is proceeding satisfactorily nor is it clear that resection and suture are required In these circumstances further diagnostic procedures are needed, namely trial section, nerve biopsy and muscle biopsy The first is the most useful since the information is immediately available and can be acted on at once. The biopsies are of more value in obscure cases of intraneural fibrosis and will be discussed under that heading.

(iv) *Trial Section*

The purpose of this procedure is to ascertain the extent of intra neural scarring. A transverse incision is made into the hardest and most prominent part of the neuroma, and gradually deepened until the first nerve bundle is met. It can always be identified before it is cut. If bundles are met near the surface it is reasonable to assume that conditions in the other apparently more normal part of the nerve will be better still The divided nerve sheath usually falls together but it is sometimes necessary to insert a fine epineural suture If on the other hand the incision reveals scar tissue it is gradually deepened until either the nerve is completely divided or until normal looking bundles are reached. In general if more than half the thickness of the nerve is involved resection and suture are indicated

(v) *Intraneural Fibrosis*

It is especially difficult to determine the correct course in those cases in which the diameter of the nerve is normal or diminished but on palpation the nerve is usually unduly firm in consistence. It is important to distinguish between *localized and diffuse lesions, the latter being commonly* caused by traction

injuries ischaemia or occasionally by intraneural injections of a noxious drug such as one of the sulphonamides Localized lesions are usually due to direct trauma or to an intraneural injection and are consequently more amenable to repair However exploration of diffuse lesions is sometimes useful in establishing the prognosis, and occasionally even an extensive lesion can be resected and replaced by an autogenous graft. Motor fibres are nearly always damaged more seriously than sensory and a positive sensory response to stimulation is no proof that useful motor recovery is likely to occur A motor response is a good sign but in its absence muscle and nerve biopsies may help and if recovery is overdue, trial section is warranted

(vi) *Muscle Biopsy*

Employment of this method requires familiarity with the histological appearance of muscle in the various phases of denervation and re-innervation (Bowden and Gutmann 1944) see p 13 The presence of axons in the Schwann tubes can often be demonstrated before there is any other evidence of re-innervation and provided that the sample is representative, their presence indicates that a good recovery is probable. Conversely irreversible atrophic changes in the muscle can be recognized and again provided that the sample is a representative one, are a clear sign that useful motor recovery is unlikely Finally the histological picture of ischaemia of muscle is characteristic and is a contra indication to repair of the nerve from the standpoint of motor recovery

(vii) *Nerve Biopsy*

In some cases of traction injury where the nerve is only moderately indurated it is sometimes impossible to distinguish by palpation between the completely fibrosed nerve trunk and one in which although there is an increase in endoneural collagen the Schwann tubes are still patent and capable of accommodating fibres of adequate size. Through a longitudinal incision a segment of a single funiculus about 1 cm. long may be removed for examination A biopsy just below the lesion may provide a guide to the adequacy of re-innervation if the time interval since injury is taken into account. The limitations of this method are twofold first, uncertainty about the representative character of the specimen and, secondly if it is found that the specimen is not seriously abnormal, some functionally useful tissue will have been sacrificed Even so there are a few occasions when this procedure is justified (Holmes and Zachary 1946)

(viii) *Lateral Neuroma*

A lateral neuroma may appear either as a single or double swelling on one side of the nerve the extreme form being a double mass with a thin lateral connecting strand of intact nerve fibres. The presence of a lateral neuroma indicates partial division of the nerve, but in addition there is often considerable disruption of fibres in the apparently intact portion The correct surgical procedure depends on the number position and importance of the apparently intact bundles for in them spontaneous recovery may occur They must not be sacrificed unless the repair of the whole nerve will provide a greater gain So many factors influence the decision that it is impossible to consider them all in detail but certain general principles can be laid down

(1) If there is evidence of conductivity in the continuous portion it should be sacrificed only if the function it serves is unimportant for example branches to

brachioradialis pronator teres or flexor carpi ulnaris are relatively unimportant and these muscles usually recover well after suture.

B 77 Radial nerve palsy due to a wound of the elbow At the time of exploration there was recovery in brachioradialis. More than two thirds of the nerve was found to be divided and a better repair was possible by sacrificing the intact portion. Brachioradialis quickly recovered.

Similarly the retention of some response in the calf muscle when the medial popliteal nerve is stimulated does not preclude complete resection and suture. On the other hand nerve bundles supplying the skin of the thumb and index finger or those supplying the carpal interossei should not be sacrificed since the quality of function regained after suture will not equal that which was originally retained.

(2) If there is no evidence of conductivity and if recovery is unduly delayed, there is a predominant element of neurotmesis in the continuous portion and complete resection and suture are indicated

(3) If there is no conductivity but insufficient time has elapsed for recovery to take place, the following considerations apply

(*a*) The consistence of the intact portion is a useful guide softness is a point in favour of preserving it, induration a point against.

(*b*) In general the condition of the nerve is worse than is apparent. In some cases where it appeared that intact bundles were passing through the continuous portion histological examination showed that they were considerably damaged.

(*c*) If more than two thirds of the nerve are divided complete resection is usually advisable. Trial section may be informative.

(*d*) If the continuous portion corresponds to an unimportant branch it may be sacrificed

6 Repair

(i) *Complete Resection and Suture*

The technique of complete resection and suture for lesions in continuity is the same as that required for complete division as a rule the gap to be closed is small and easily closed and it is always possible to preserve the correct orientation of the nerve stumps.

(ii) *Partial Resection*

Where total resection is unjustifiable partial resection and repair are worth attempting. There are two methods, the loop suture and the inlay graft. It is desirable that there should be a fairly clear line of cleavage between the intact and the damaged portions of the nerve, but this is not a common occurrence. Loop suture is awkward in that the portions to be sutured have no proper sheath on one side, so that approximation is seldom perfect. In addition the intact portion of the nerve may be stiff and oedematous and difficult to loop with the result that it may be damaged or the suture line may open out Loop suture finds its best application where a nerve readily splits into two for example the ulnar and sciatic nerves near their terminal bifurcations and the median nerve immediately below its origin in the axilla.

In other situations the inlay graft is better (see Chapter IX)

7 Neurolysis

The term neurolysis implies freeing the nerve usually from scar tissue surrounding it. Thorough exploration of the nerve with sufficient mobilization of the lesion to permit inspection and palpation in itself constitutes a major part of the procedure. It only remains to replace the nerve in a healthy bed It may be necessary to transpose it or to excise scar tissue so that the nerve can lie in a clean intermuscular plane There has been no evidence that wrapping the nerve in foreign material in any way protects it indeed numerous examples have been met of the adverse effects on the nerve of enclosure in tantalum foil cellophane, amnioplastin and fascia lata

It is usually impossible to prove that neurolysis in itself has been responsible for any subsequent improvement but there are a few occasions when a band of scar runs across the nerve and appears to be constricting it, or when the nerve is clearly distorted and compressed by a fragment of bone Then it is tempting to ascribe subsequent improvement to the operative procedure and the possibility cannot be denied if the interval between neurolysis and recovery is compatible with the time required for regeneration from the level of the lesion However it is certain that many of the recoveries often dramatic, after neurolysis were coincidental and would have occurred without operation There are, of course, a number of well recognized conditions in which freeing of the nerve from external pressure undoubtedly arrests degenerative changes and may allow recovery to occur The most common example is traumatic ulnar neuritis in which the progress of degeneration may be halted and even reversed by anterior transposition of the nerve

The use of internal neurolysis—by longitudinal incision of the sheath of the nerve or by the intraneural injection of saline—has little to support it either in theory or in practice Occasionally an intraneural foreign body can be removed but in this case there is always a partial division of the nerve and it is the extent of the partial division rather than the presence of the foreign body that governs the choice of conservative or radical treatment.

8 Conclusions

Complete paralysis following open wounds is due to complete or partial division of a nerve in a high proportion of cases incomplete paralysis following open wounds is also often the result of partial division. Consequently all nerve lesions due to open wounds where the clinical picture is compatible with a complete or a serious partial division should be explored as soon as possible after the wound has healed Closed injuries do not often cause lesions requiring repair However exploration should be performed if there is delay in recovery a possibility of persistent compression, or regression of function also in some instances of pain, and in selected cases of paralysis due to traction ischaemia or intraneural injection

Exploration of a nerve is seldom if ever regretted but neglect of it frequently has serious consequences. If on exploration, the exact state of the nerve is still in doubt but it seems likely that there has been extensive neurotmesis trial section may be required to establish the diagnosis

Repair by complete resection is often indicated in lesions in continuity but alternative methods are available if the intact portion of the nerve is too important to be sacrificed.

PART II. NERVE INJURIES AND FRACTURES

by D M Brooks

1 Introduction

Nerve injuries are often associated with fractures, and although they are not specifically war injuries, a discussion of nerve lesions in continuity would be incomplete without some reference to them. The relationship between the usual types of fractures and nerves injuries can be accurately determined only in an accident or a fracture centre Seddon (1947a) for example, gives figures from a general accident service which show that in a consecutive series of 102 fractures of the upper limb there were two serious and five minor nerve injuries.

The other side of the picture the incidence of fracture as an accompaniment of nerve injury is derived from an analysis of cases at one of the centres

Total number of nerve injuries 2,969
Number associated with fractures 955 (32 1 per cent)

However a large number (755) of palsies accompanied by fractures were due to wounds by missiles this association is most common in radial and posterior interosseous lesions and least frequent in the lower limb and in injuries of the musculocutaneous and circumflex nerves (Table 25)

TABLE 25

Incidence of fractures in nerve injuries due to gunshot wounds

Nerve	Number of cases	With fracture	
		No	Percentage
Median	498	141	28
Ulnar	737	209	28
Radial	374	169	45
Posterior interosseous	*88*	*58*	62
Musculo-cutaneous	26	3	11 5
Circumflex	27	3	11
Femoral	2	1	50
Medial popliteal	467	89	19
Lateral popliteal	570	102	18
Total	2,789	775	

The outlook in these cases is determined more by the nature of the wound than by the presence of a fracture.

In the group of 2,969 nerve injuries mentioned above, only 180 were associated with fractures not due to gunshot wounds and this is the group in which the relationship between nerve injury and fracture can most fruitfully be studied

2. Mechanism

A nerve may be injured either when a bone is broken or at a later date if an imperfect union leads to deformity e g. condylar fractures of the humerus leading to traumatic ulnar neuritis. In the first group of cases, the cause is

traction or compression in the second mainly friction The distinction between traction and compression injuries is important not only because the prospects of spontaneous recovery are bad after severe traction injuries but also because a severe lesion due to compression being more localized is generally susceptible of repair

The recognition that a palsy is due to traction is aided partly by the distribution of the paralysis and partly by the nature of the fracture or dislocation with which it is associated If the paralysis is due to a nerve injury proximal to the fracture site, the cause of it must be traction if it affects more than one nerve trunk, traction again is probably responsible Dissociated palsies, e g. motor paralysis with sensory sparing in a proximally situated lesion are more frequently due to traction than to compression.

The nature of the injury to the limb may indicate equally clearly that traction has occurred, e g. if a closed injury of the knee damages the lateral ligament or ruptures the tendon of biceps the joint must have adducted, and any accompanying paralysis of the lateral popliteal nerve is due to traction In central dislocation of the hip on the other hand there is shortening of the course of the sciatic nerve rather than stretching, and the paralysis in such cases is due to compression of the nerve by fragments of the disrupted acetabulum

However it is sometimes impossible to decide on clinical grounds whether the lesion is due to traction or compression or perhaps to a combination of the two forces. Dislocation of the shoulder may cause circumflex paralysis by the displacement of the nerve by the head of the humerus and this could be due to traction or to compression However the subsequent behaviour of these lesions is so frequently characteristic of a traction injury that this seems the more likely cause recovery is often slow and the paralysis is sometimes permanent

(i) *Traction Injuries*

Seddon (1947a) has pointed out that in many instances the fracture is not the immediate cause of the paralysis but is itself produced by the same force that causes the nerve injury Thus in a brachial plexus paralysis associated with fracture of the clavicle the latter is incidental and may have contributed nothing to the damage suffered by the plexus. The downward distraction of the shoulder is the cause of the nerve injury which can be just as severe and extensive without a fracture as with one. Similarly in lateral popliteal palsy due to adduction of the leg, an avulsion fracture of the head of the fibula has no aetiological significance. In other situations, however a fracture or a similar structural upset is an essential element in the picture, or at any rate contributes to the seriousness of the nerve injury A traction injury of the circumflex nerve does not occur unless there is dislocation or fracture-dislocation of the shoulder

An unusual association of fracture and nerve injury is that which sometimes occurs with a transverse fracture of the shaft of the humerus. The distal part of the limb is then supported only by soft tissues and if a sharp pull on the arm immediately follows the fracture it may cause a traction lesion in continuity or even rupture of the nerve trunk.

Fractures of the humerus or femur with much angulation may cause nerve injury and it is often difficult to decide whether traction or compression is mainly responsible. The association of fractures and traction lesion may be summarized as follows

Nerve injury	*Fractures and dislocations*
1 Brachial plexus	Clavicle Shoulder
2. Circumflex	Shoulder (with or without fracture of the upper end of the humerus)
3 Radial or median	Shaft of humerus
4 Sciatic	Hip (posterior fracture or fracture-dislocation)
5 Sciatic	Shaft of femur (rare)
6. Lateral politeal	Avulsion of head of fibula

(ii) *Compression Injuries*

Examples of paralyses due to either traction or compression have already been mentioned Compression is probably not important in circumflex palsy accompanying dislocation of the shoulder but it is the main cause in paralysis complicating *a fracture of a long bone with angulation or displacement of the* fragments. Compression injuries are often produced by a momentary crushing of the nerve between one fragment and the external object that causes the fracture. Sometimes the nerve is nipped between the bone fragments and may remain compressed between them until released at operation or it may be completely severed At other times, the nerve is displaced by a bone fragment and, being unable to resume its normal course, remains subjected to pressure and may require open operation for its release.

Neurologically the chief characteristics of compression of a nerve due o a fracture are that the paralysis is referable to a lesion at the level of fracture recovery is usually good and a dissociated type of paralysis is not common.

3 Spontaneous Recovery

The return of a flicker of activity in a few muscles or of deep sensibility in part of a previously analgesic zone, does not constitute satisfactory spontaneous recovery *Indeed, even if the proximal muscles recover sufficiently to act against* gravity and pain sensibility returns throughout the affected zone of skin, the result is inadequate and a better one can usually be expected after nerve suture. Spontaneous recovery for present purposes *is therefore regarded as the* attainment of function not far short of normal, and generally better than could be expected after the most satisfactory suture

Table 26 shows the prospects of spontaneous recovery in nerve injuries complicated by fractures, where the cause was thought to be compression.

An important feature of this collection of cases is that the presence of a wound making the fracture open or compound, had no bearing whatever on the prospect of spontaneous recovery the proportion of cases recovering well was *exactly the same whether the injury was open or closed* Thus there is a sharp distinction between the open fracture with nerve injury caused by a missile where the prospect of complete division of a nerve or something approach ing it is about 50 per cent (*Foerster 1929a* Spurling and Woodhall, 1946* Seddon 1949a) and the ordinary open fracture with nerve injury where the

* *Quoted Wexberg (1935b) S.T*

prospect of serious damage to the nerve is about 20 per cent. In the first the nerve is injured by the missile and the fracture is incidental in the second the nerve is injured by the broken bone, and the rupture of the skin is incidental

It will be noted that the proportion of recoveries after injuries of the circumflex nerve is singularly low and this is probably due to their being caused by *traction* rather than by compression and to that extent it is questionable whether they should be included in the table Seddon (1947a) has explored two cases of circumflex paralysis due to closed injuries of the shoulder *in both the nerve* was in continuity In the one case in which biopsy was performed there was histological evidence of *damage by traction.*

The radial nerve calls for special mention since it is more frequently injured than any other and the management of these lesions provides the clue to the treatment of all nerve injuries directly consequent on fractures. It is clear that there is no justification for routine exploration of all cases of complete radial paralysis caused by *fractures* of the shaft of the humerus since seven out of ten make an excellent recovery spontaneously

TABLE 26

Incidence of spontaneous recovery in nerve injuries due to compression and complicated by fractures

Nerve	Number of cases	Spontaneous recovery	
		No	Percentage
Brachial plexus	1	1	100
Radial	44	31	70
Posterior interosseous	6	6	100
Median	8	8	100
Ulnar	12	10	83
Circumflex	2	1	50
Medial popliteal	14	12	86
Lateral popliteal	15	12	80
Total	102	81	79

in fact occurring. Fig. 44 shows a case in which the fracture is 12 cm. abov epicondyle of the humerus. The point of entry into brachioradialis of its n branch is about 2 cm above the epicondyle regenerating axons must ther travel a distance of at least 100 mm. before there can be any sign of re-inn tion of this, the most proximal muscle. No recovery can be expected in less 100 days and one would be justified in waiting for say 130 though hardl longer in order to allow for possible fortuitous delay By this time the hun

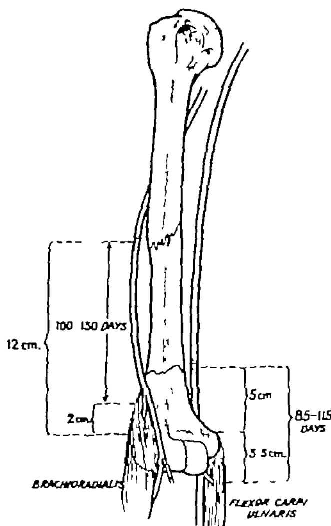


Fig 44 Diagram showing how the interval before exploration of a nerve is calculated in cases of nerve injury due to fracture of the humerus.

should be well united the plaster will have been removed and the opportun taken to restore movement in the elbow Clinical examination and, if requir electro-myography will show whether recovery is occurring or not. Absence recovery after the predicted date is a clear indication for exploration and o may find a state of affairs such as is illustrated in Fig. 45

A compound fracture calls for the usual early operative treatment whether not a nerve injury is present No special search should be made for the ner during the excision of devitalized muscle and other tissues, but if it is expos

III

PART I. HISTOPATHOLOGY OF NERVE INJURY

by W BLACKWOOD and W HOLMES

1 Introduction

AN individual nerve fibre may suffer one of three grades of damage from local trauma. These were described by Seddon (1943) as neurapraxia, axonotmesis and neurotmesis, and although his original intention was to employ these terms as a basis for clinical diagnosis they have, in fact, proved more useful in the pathological classification of injuries of individual nerve bundles or fibres and will be so employed here

(1) *Neurapraxia* interference with function unaccompanied by degeneration of nerve distal to the injury but probably associated in the more severe cases with interruption of continuity of the myelin sheath at the level of the injury (Denny Brown and Brenner 1944 a,b,c)

(2) *Axonotmesis* division of the axon with peripheral degeneration of both axon and myelin sheath, but without appreciable damage to the neurilemmal and endoneurial sheaths.

(3) *Neurotmesis* complete disruption of the essential elements of the nerve, though not necessarily accompanied by gross solution of continuity

In injuries of nerves the practical histological unit is not, as a rule, the nerve fibre within its endoneurial sheath, but rather the bundle of fibres within its perineurial sheath. A large nerve is composed of several bundles bound together by a fibrous epineurial sheath. In the experience of the writers the nerve fibres within the individual bundles were usually but not always, affected to a similar degree, whether by neurapraxia, axonotmesis or neurotmesis Although in some cases the bundles composing a nerve all showed similar histological changes, in others the bundles showed variation in the degree of damage, some even being undamaged (Fig. 74). Such lesions cannot be fitted neatly into any one of the three divisions of neurapraxia, axonotmesis or neurotmesis.

In the opinion of experienced clinicians, the appearance and consistency of the nerve at operation is a guide to prognosis (Chap. II) but in the fixed material available to us, no clear correlation seemed to exist between the histological and the naked-eye appearances of the lesions. The partially separated ends of a nerve were sometimes joined by pale tissue which might require histological examination to show the relative proportions of undamaged nerve bundles, neuromatous tissue or fibrous scar (Fig. 46) in





FIG 46. Segment of lateral popliteal nerve injured seven months previously Paralysis was complete. At operation the proximal stump (*right of picture*) and the distal stump (*left*) were united by tissue which to the naked eye was of indefinite nature. Histologically it was vascularized fibro-fatty tissue and was not innervated—complete nerve division.

other cases the stumps were widely separated An important factor in modifying the appearances, both gross and microscopical was the time that had elapsed after injury (Figs. 47–50)

Even separation of the lesions according to the naked-eye appearances into *lesions in continuity* and *complete division* is open to objection from the histological point of view for the naked-eye appearances may be most misleading An apparent *lesion in continuity* may prove on microscopical examination to consist of histologically separate stumps joined by scar tissue only and to

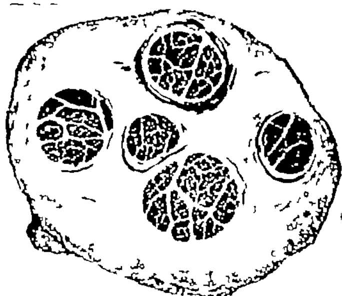


FIG 47

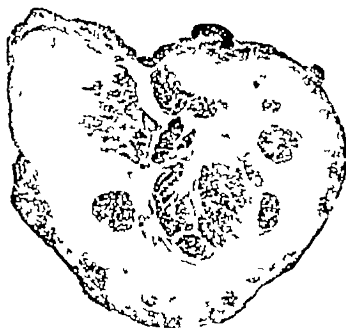


FIG. 48

FIGS. 47 and 48 Transverse sections of proximal and distal stumps of an ulnar nerve completely divided six weeks previously Perineurial fibrosis is present in both. In the distal stump there is oedema and all the nerve fibres are degenerating. Note that there is very little shrinkage of the distal face. Myelin stain. 12 mm. = 1 mm.

belong in fact to the category of *complete division*. Furthermore, nerve ends which, at an early stage, may be completely separated are sometimes united later by a neural outgrowth from the central end. Indeed it is exceptional to find a nerve that has been divided for several months that does not show at least a trace of re-innervation of the distal stump (Figs. 51–60)

These findings are sufficient to indicate the futility of attempting to make an elaborate pathological classification of material obtained at operation, and it is more profitable to consider all the available evidence, most of it experimental which throws light on the mechanisms involved in the several types of nerve injury and repair

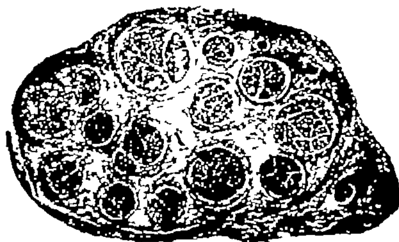


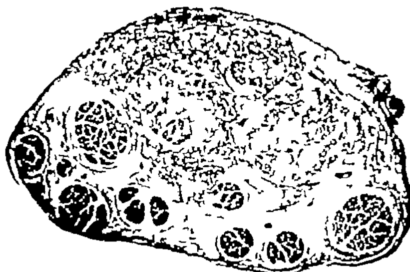
FIG. 49



FIG. 50

FIGS. 49 and 50 Transverse sections of proximal and distal stumps of a posterior tibial nerve completely divided ten months previously Regenerating fibres are not present. *With the passage* of time the distal face has shrunk. Most of the myelin debris in the distal stump has been removed. Myelin stain. 16 mm. = 2 mm.

FIG 51



FIGS. 51 and 52. Transverse sections of the proximal and distal stumps of a median nerve injured by a bullet four and a half months previously At operation the nerve ends were 1 cm apart, both embedded in pronator teres. Part of the proximal stump has fanned out into a neuroma The section of the distal stump is incomplete Myelin stain 11 mm.=1 mm.



FIG 52

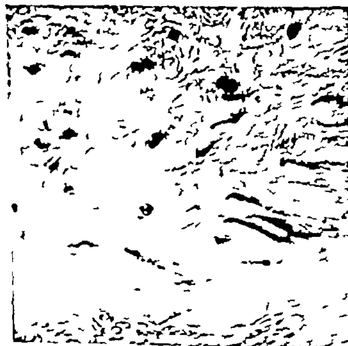
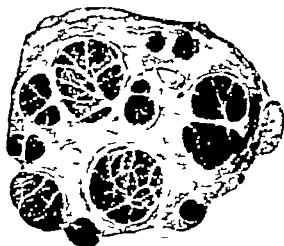


FIG 53 Transverse oblique section of part of the distal stump of the the same nerve showing that, despite the appearances at operation, some nerve fibres had, in fact, grown down into it Myelin stain 15mm=20μ.



FIGS. 54 and 55 Transverse sections of the proximal and distal stumps of an ulnar nerve injured by a shell splinter twelve months previously. At operation the nerve appeared to be completely divided with gap of several mm. between the ends. Myelin stain 12 mm = 1 mm.



FIG 55



FIG. 56. Transverse section of part of the distal stump of the same nerve, showing that, despite the appearances at operation, many nerve fibres had, in fact, grown down into the oedematous distal stump. Myelin stain 15 mm. = 20μ.

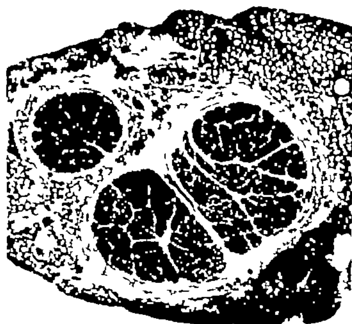


FIG 57



FIG 58

FIGS. 57 and 58. Transverse sections of the proximal and distal stumps of an ulnar nerve divided by a severe cut *four years* previously At operation the nerve ends were far apart, being joined only by a slender column of tissue thought to consist of scar tissue with probably a few nerve fibres. *Histologically* this junctional tissue was richly innervated Note the shrinkage of the distal face Myelin stain 1 mm. = 18 mm.



FIG. 59

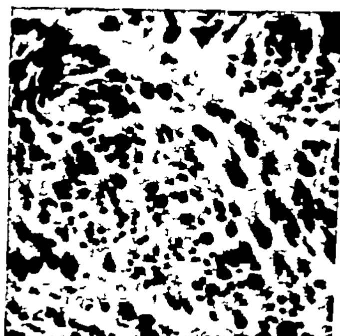


FIG 60

FIGS. 59 and 60 Transverse sections of part of the proximal and distal stumps of the same nerve Both stumps are innervated, the proximal by myelinated fibres only a little *smaller than normal, the distal by smaller fibres. The distal stump is still* oedematous all myelin debris has been removed. There was still complete paralysis except for flexor carpi ulnaris. Myelin stain. 18 5 mm. = 50 μ.

2. Experimental and Clinical Studies of Degeneration and Regeneration

(i) Neurapraxia

Contusion of a nerve may be due to a transient blow such as is given by a passing projectile or bone fragment, or in a closed injury by trauma which exerts its effect through the tissues surrounding the nerves

The aetiology of contusion lesions in gun shot wounds has been demonstrated by Puckett Grundfest McElroy and McMillen (1946) Twenty-one cats under deep anaesthesia were shot in the thigh by a small high velocity steel sphere, the gun being aimed so that the sphere would pass through the thigh near to the sciatic nerve but without touching it. The nerve was made radio-opaque by the injection of a contrast medium before the shot was fired Radiographs showed that even when the shot passed through the thigh at a distance of more than 1 cm from the sciatic, the nerve was pushed aside extremely rapidly The acute functional consequences of the injury were determined by electrical stimulation of the nerve at the level of the sciatic notch In 15 cases in which the missile had passed at a distance of from 1 5 to 2 5 cm from the nerve there was no evidence of impaired motor conductivity In four cases in which the missile had passed within about 1 cm. of the nerve, conduction was blocked at the level of the wound track. Six hours later when the experiment was discontinued the block was still present.

Denny Brown and Brenner (1944 a) studied the effects of a local blow on the sciatic nerve of the cat the exposed nerve being gently raised on a flat metal surface. Histological study of the specimens revealed varying degrees of damage in the different experiments, and by correlation of functional and histological findings it was possible to construct a series showing the effects of progressively more serious contusion

In one group of experiments motor paralysis lasted six weeks or longer and there was Wallerian degeneration of all myelinated fibres distal to the lesion, i e. an axonotmesis Some sensory sparing was invariably present.

In the other group an immediate and more or less complete motor paralysis persisted for three to four days but recovered rapidly on the fifth or sixth except for some hyperaesthesia to light touch no impairment of sensibility could be detected when the animal recovered from the anaesthetic 18 hours after injury The nerve was swollen at the site of injury the amount of swelling corresponding with its severity The most striking change at the site of injury was in the sheaths of the larger myelinated fibres after three days the myelin was either swollen and feebly staining or in a state of dissolution, while that of the smaller fibres appeared to be unaffected On the fifth day myelin sheaths in all stages of degeneration were found at the site of injury and the axons lay either completely denuded or with only a remnant of myelin on their surfaces. The demyelinated gap varied from 0·01 mm. to 1 1 mm. in length the naked axons showed no fibrillation and did not put out branches. The small myelinated fibres from 2 to 3 μ in diameter appeared intact. This seems to be the characteristic histological picture of neurapraxia.

Since swelling of the nerve is a feature of these lesions it is appropriate to refer here to the work of Weiss (1943c) on the origin of endoneurial oedema He considers that the oedema which results from constriction is due to obstruction of the centrifugal flow of fluid in the endoneurium which normally takes place along the whole nerve trunk but this view is not supported by the work of Denny Brown and Brenner who believe that the oedema is a local vascular phenomenon

The reader wishing to pursue the subject further should also consult the papers of Denny Brown and Brenner (1944 b c) on the effects of direct compression of nerve by a mercury bag and by spring clips and a paper on the histological consequences of compression by Causey (1948)

(ii) *Axonotmesis*

The most satisfactory method of producing axonotmesis experimentally is by crushing a nerve trunk with fine smooth-tipped watch maker s forceps pressure is applied firmly for some seconds The axons myelin and Schwann sheaths are *thus divided the connective tissue sheaths are distorted but not interrupted*, with the result that the tubular endoneurial sheaths ('Schwann tubes) are continuous through the injured zone. After axonotmesis, therefore the outgrowing streams of axoplasm from a particular fibre are free to flow down the Schwann tube occupied by the remains of its distal segment, and cannot escape from it. At first there may be many sprouts within one tube, though each is connected to the single parent axon. Sooner or later however all but one disappear the factors determining which survives will be described later (p 107) Axonal sprouts which fail to grow straight down the walls of the tube are those which are blocked or diverted by obstacles and disorientated surfaces within the tube These sprouts may terminate as blobs of axoplasm against Schwann cells or macrophages, or may form bizarre structures such as the spirals of Perroncito These abortive sprouts appear to be reabsorbed earlier than the accessory fibres which grow straight down *the tube, for they can seldom be found after the first few weeks of regeneration.*

The process of regeneration depends on the steady advance of the axons down the distal nerve to the end-organs, and this process might well be supposed to require a continuous synthesis of new axoplasm, commencing as soon as outgrowth begins. In fact, however it has been found that the earliest sign of outgrowth the break up of the cut end of the axon into strands, is not an out growth at all but the appearance of discrete neurofibrils which must be assumed to be due to a change which causes the normal longitudinal orientation of the substance of the axon to become visible microscopically

Next comes the period of true outgrowth. It was found (Gutmann and Sanders, 1943 Sanders, 1948) that the axoplasmic outflow during the first 100 days of regeneration in the rabbit is due only to depletion of the proximal axons for there is no evidence that new material is synthesized After 100 days *both proximal and distal axons increase in diameter together* new axoplasm must be in the process of manufacture somewhere in the length of the regenerating neuron

One clinical example of axonotmesis was seen

A through-and-through bullet wound of the right upper arm caused a median nerve palsy and damaged the brachial artery Ten weeks later the damaged segment of the right median nerve was removed (Fig. 61) The proximal face contained nine nerve bundles. One medium-sized bundle was well innervated by large myelinated fibres the other eight showed occasional large myelinated fibres, but for the most part there was Schwann cell proliferation within the endoneurial tubes, which contained numerous fine regenerating myelinated fibres and also occasional globules of degenerating myelin (Fig. 62). Longitudinal sections of the middle part of the resected specimen showed fine regenerating nerve fibres everywhere running within *intact perineurial and endoneurial sheaths.* Near the distal end of the specimen, they became less mature, that is, their calibre was diminished. At some undiscovered point, the one normal bundle had been injured, for the distal face did not contain any large myelinated fibres. It was oedematous and within the perineurial sheaths, focally thickened by fibrous tissue, lay the endoneurial tubes, in which the Schwann cells had proliferated (Fig. 63). A moderate number of the tubes contained fine myelinated nerve fibres, *for the most part finer than those* in the proximal face many contained myelin débris. The picture was one of axonotmesis and regeneration after trauma which had been maximal close to the lower end of the specimen.

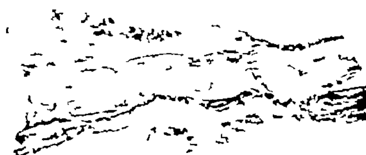


FIG 61 Lesion in continuity Segment of a median nerve injured ten weeks previously Longitudinal section showing the undisturbed course of the nerve Myelin stain 2 cm. = 5 mm.

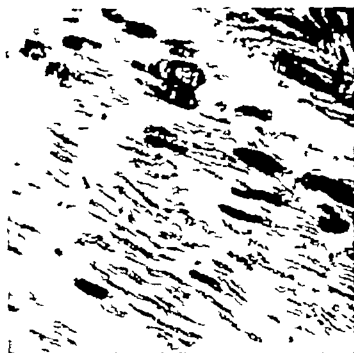


FIG 62. Oblique transverse section of part of the proximal face of same nerve. The endoneural tubes are mostly innervated by fine myelinated fibres, but some contain large myelinated fibres (right centre). A few globules of degenerating myelin persist in some tubes (*top centre*). Myelin stain. 12 mm. = 50μ.

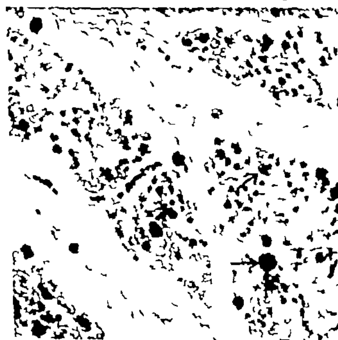


FIG 63 Transverse section of part of the distal face of same nerve same magnification Groups of endoneural tubes, filled with proliferated Schwann cells, are separated by oedema. Some endoneural tubes contain large globules of degenerating myelin (*lower arrow*) some may contain axons but they are not myelinated some contain single myelinated fibres of a calibre less than is seen in the proximal face others contain 2–3 myelinated fibres (*upper arrow*) Myelin stain 12 mm. = 50μ.

(iii) *Neurotmesis*

Complete section of a nerve trunk by means of sharp scissors is the standard method of producing experimental neurotmesis, and is a preliminary to the *study of repair by suture.*

If a length of nerve is then excised the regenerative outgrowth from the proximal end may form either a typical neuroma, or a more diffuse outgrowth with little or no swelling of the nerve end The most swollen portion of a neuroma is a new formation composed of a convoluted mass of outgrowing axons many develop beyond the fine filamentous stage, but never reach a normal diameter Each sprout is closely followed by Schwann cells which emigrate from the proximal stump and move along the surface of the axon. Fibroblasts and blood vessels also follow The axons then lie in Schwann tubes reconstituted by the supporting cells but the perineurium is not reformed and the nerve fibres are never therefore collected into bundles. Often the neuroma is completely encapsulated in a fibrous sheath formed by proliferated epineurial fibroblasts this process is less complete when the adjacent tissues have been damaged, and there are then fibrous adhesions between the neuroma and the nerve bed In such cases axons escape from the neuroma and invade adjacent tissues. When this occurs on a large scale the bulb is less well marked for its size is partly due to the doubling back of the abortive sprouts and partly to endoneurial oedema, both of which processes are less pronounced when the nerve end has not been encapsulated

The alternative mode of outgrowth leads to the formation of an elongated strand of regenerated nervous tissue, with perhaps little or no swelling at the end of the proximal stump The strand grows along a tissue plane and may spread out as a flat sheet over intact muscle or fascia. In this way long stretches of new nerve can be formed though they lack the normal architecture and they may connect proximal and distal stumps across remarkably extensive gaps. This form of outgrowth is most common when the nerve lies in an undamaged bed, for an encounter with inflammatory or scar tissue diverts the flowing axons and prevents their forward advance

Examination of material from clinical cases (from three weeks after injury onwards) revealed once more the largely familiar appearances. At first, in the gap between the upper and lower stumps, there is blood clot and sometimes muscle, bone, or foreign bodies The blood clot becomes organized and elongated cells resembling both fibroblasts and Schwann cells grow into it from the stumps (Fig 71) The difficulty of differentiating between these two cell types makes their relative numbers a matter of dispute. The outgrowth from the distal stump is greater and its constituent cells are more parallel In a few days the axons of the proximal stump of the nerve begin to flow down towards and into the gap (Figs. 64–69) whilst the thickness of the axons and myelin coats of the parent nerves diminishes. Obstruction leads to division of the axons so that there are soon numerous fine branching fibres, which flow out into the neighbouring tissues and follow the lines of least resistance along cellular and fluid interfaces. This results in outgrowth in all directions, even to the curious retrograde spirals of Perroncito (Fig. 70) The axonal outgrowths are accompanied and surrounded by outgrowths from the cells of the sheaths and this widespread outgrowth together with the cellular proliferation and oedematous swelling, constitutes the neuroma (Figs. 72 and 73) The oedema, which may also be present in a distal stump during re innervation often persists for many months. The products of Wallerian degeneration in the distal stump are removed



FIG 64 Longitudinal section of excised segment of an ulnar nerve divided by a cut 15 days previously From the left, axons are growing out into the cellular tissue which fills the space between the stumps. The distal stump is just out of the picture on the right Hortega neurofibril stain. 18 mm = 2 mm.



FIG. 65 Longitudinal section of proximal stump of same nerve, showing principally beaded and degenerating myelin. This myelin extends to within a short distance of the end of the proximal stump. Myelin stain. 2 cm. = 0·3 mm.



FIG. 66 Fellow section to Fig. 65, showing irregular axonal outgrowth into the cellular tissue which fills the space between the stumps. Hortega neurofibril stain. 2 cm. = 0.3 mm.



FIG. 67 Proximal stump of same nerve at another level showing axonal outgrowth. Note the forked outgrowth right centre. Hortega neurofibril stain. 16 mm. = 0.2 mm.

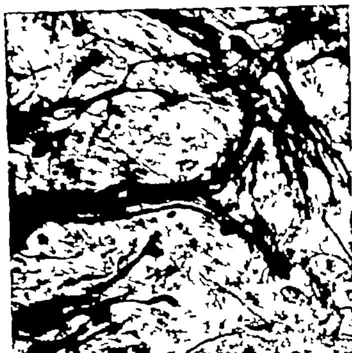


FIG 68. Higher power view of forked axonal outgrowth seen in Fig. 67 The axonal outgrowth is influenced by the arrangement of the cells filling the space between the stumps. Here both the cell pattern and the course of the axonal outgrowth lack orientation Hortega neurofibril stain. 17 5 mm. = 50 μ.

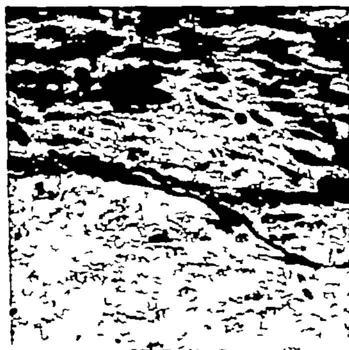


FIG 69 Axonal outgrowth from the proximal stump Here many of the supporting cells point in the same direction and the axonal out growths pursue a straighter course. Hortega neurofibril stain. 17 5 mm. = 50 μ.

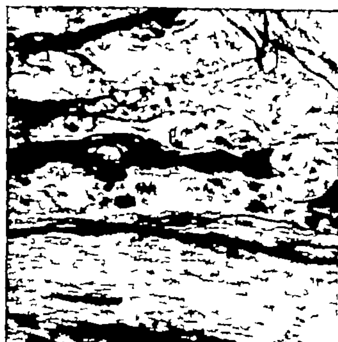


FIG. 70 Axonal regeneration in the proximal stump Below the middle of the picture a regenerating axon passes, in smooth curves, over the surface of Schwann cells within a neurilemmal tube. Above this in the picture, a larger axon, also growing towards the right, divides to pass a globule of degenerating myelin (shown as a vacuole) Beyond this the axonal stream re-unites. Further on a serious impediment results in retrograde flow of fine axonal filaments, producing a formation akin to a spiral of Perroncito Hortega neurofibril stain. 17 5 mm. = 50μ.

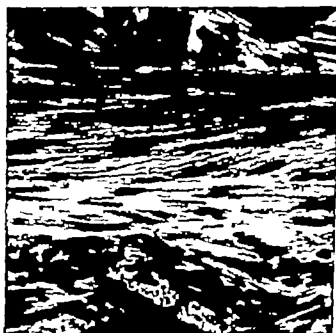


FIG 71 Cellular outgrowth from the distal stump, consisting of parallel-running spindle-shaped cells. Silver impregnation. 17 5 mm. = 50μ.

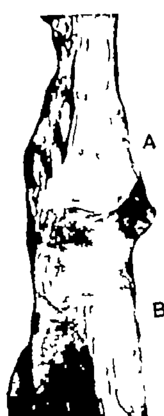


FIG 72. Longitudinal section of a sciatic nerve divided by a bullet six months previously Cellular and neural outgrowth from the proximal stump have produced a neuroma at A whilst from the distal stump B there is an obliquely running cellular outgrowth or glioma' A portion of muscle almost separates the neuroma and the glioma



FIG 73 Stump neuroma in a digital nerve divided six months previously The axonal outgrowths are myelinated, but have not found the distal stump Of lesser calibre than their parent fibres, they fan out and interweave in patternless confusion Myelin stain 10 mm = 1 mm.

by phagocytes, though it may be many months—even up to two years—before the distal endoneurial sheaths are cleared of degenerating myelin In time these sheaths, if not re innervated grow narrower and fibrous tissue increases in their walls. Within them from soon after the injury the Schwann cells increase in number and at the cut ends they form part of the cellular outgrowth or *glioma* which grows towards the proximal stump (Figs 71 and 72) If the cellular outgrowths from the two stumps join a tortuous pathway is provided which guides axonal outgrowths into the distal endoneurial tubes If the outgrowths do not come into contact the axons will pass in many directions into the scar tissue between the stumps, forming a stump neuroma, though a few fibres will reach the distal stump and may there grow alongside rather than into the endoneurial tubes The lumen of the endoneurial tubes and the diameter of the cross-section of the distal part of such a poorly re innervated nerve will decrease in size (Figs 49 and 50 p 90)

If axons do reach the distal part of the nerve they will grow down the Schwann cell filled endoneurial tubes. Initially several outgrowths may be flowing down one tube but ultimately the outgrowth that first reaches the end-organ especially if it is an appropriate one, will grow larger whilst the others atrophy Myelination of the outgrowths spreads from the parent fibres towards the periphery

As the axonal outgrowths increase in diameter so do their myelin sheaths, but only a few of the fibres in the distal part of the nerve will become as large as those in the proximal

(iv) *Incomplete Division*

An incompletely divided nerve is one in which the injury has affected only part of it this includes cases in which (1) some fibres have suffered such damage that there will only be degeneration and replacement of internodal segments of myelin without any break in continuity of the axon (neurapraxia) (2) some axons, and consequently their myelin sheaths, have suffered interruption (axonotmesis) (3) some fibres have suffered interruption of axon myelin neurilemmal and endoneurial sheaths, that is, neurotmesis involving perhaps all the fibres in one or more of the bundles composing the nerve As long as there is any intact perineurium, the lesion will be one of partial division.

A typical example of partial neurotmesis with partial axonotmesis is provided by the following case

A man suffered a through-and-through bullet wound of the arm, which fractured the humerus and caused radial paralysis. Four months later there was a little return of power in extensor carpi radialis longus. Exploration carried out at this time showed a lateral neuroma and glioma (Fig. 39 p 61) which was characteristic of partial division. It was decided that complete resection and suture was the appropriate treatment. Histologically the proximal end of the specimen showed oedema of one bundle, and uniform innervation by myelinated fibres of diameters that were mostly subnormal. The line of resection had, therefore, passed through the zone of retrograde degeneration, though there were no relics of it in the form of myelin remains. The distal face was slightly oedematous. About one third of the bundles were innervated with very small fibres, most of them 4 μ or less in diameter the remaining bundles contained very few fibres. A longitudinal section (Fig. 74) showed the typical double lateral hump and in the part of the nerve remote from it a few bundles in continuity The projections exhibited the usual appearances of a neuroma and of a glioma The intact bundles contained numerous regenerating fibres, such as are seen in experimental axonotmesis. The decision to resect this lesion was correct in view of the finding that two thirds of the thickness of the nerve had been involved ordinary suture was technically more satisfactory than an attempt to free the intact bundles from those that had been divided, with repair of the gap in the latter by inlay grafting.

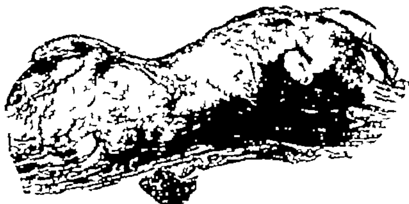


FIG 74 Longitudinal section of segment of a radial nerve injured four months previously by a bullet. Some nerve bundles which are intact can be seen in the lower part of the picture. Other bundles are divided and the resulting neuroma and glioma are seen above. Myelin stain ×5 (See Fig. 39)

(v) *Schwann Cell Outgrowth*

The emigration of Schwann cells from the distal stump of cut nerves was noted by Nageotte (1922) Masson (1932) and others. Young, Holmes and

Sanders (1940) showed that where proximal and distal stumps were left separated by an interval of 15 mm in an undamaged uninfected field the gap was bridged in 15 days. Schwann cell outgrowth from the distal tubes plays a major part in forming the bridge of nervous tissue between the stumps, and hindrance of this process due to the formation of collagenous fibrous tissue at a suture line will cause deviation of the Schwann outgrowth and so decrease the completeness of the union

In animals the columns of Schwann cells emigrating from the distal tubes frequently show a palisade arrangement and it was this appearance that led Masson to call them peripheral gliomas In specimens of human suture lines however it is extremely difficult to distinguish between Schwann and fibroblast outgrowths indeed, Denny Brown (1946) has concluded that perineurial fibroblasts have a certain rôle in the formation of satisfactory junctions, since they tend to grow out in such a way as to maintain the longitudinal orientation of the tissue connecting the stumps.

Abercrombie and Johnson (1942) examined the problem of Schwann cell emigration by experiments *in vitro* The cells of normal nerve show little activity in tissue cultures. When the nerve is cut the Schwann cells of the distal stump begin to be active after two days, and after the fourth day activity rises rapidly and reaches a peak on the nineteenth to twenty fifth days. Activity then falls quickly up to about the sixtieth day and then more slowly The half centimetre of the stump closest to the cut is at first more active than the further distal portions of the nerve.

The Schwann cells of the peripheral glioma provide ideal surfaces for the conduction of the regenerating axons into the distal tubes, as well as for the reformation of the nerve fibres, and if other conditions are satisfactory the best time for suture is when the most rapid Schwann outgrowth is taking place Abercrombie and Johnson s figure of 19 to 25 days after division is closely paralleled by the observations of Holmes and Young (1942) who found that the best unions were made when suture was performed from 14 to 21 days after division Holmes and Young (1942 and later work) also found it desirable to leave a small gap—1 to 2 mm —between the sutured stumps, for if the proximal and distal faces are pressed together the ends of the nerve tubes are deformed and diverted from their normal longitudinal orientation so in consequence are the axonal and Schwann cell outgrowths

(vi) *Wallerian Degeneration*

The well known sequence of events in the destruction of fibres separated from their cell bodies has been redescribed by Holmes and Young (1942) The activities of the Schwann cells which multiply and form long strands of cytoplasm are an essential part of the preparation for the reception of new axons and the formation of new fibres. Abercrombie and Johnson (1946) have studied the proliferation of the cells within the Schwann tubes and also that of the cells in the endoneurium In the rabbit s sciatic nerve most of the changes in cell populations take place within the Schwann tubes and not in the endoneurium The total nuclear population in tubes and endoneurium together remains stationary during the first three days of degeneration it then rises gradually to a peak value of about eight times the initial population which is achieved after 25 days of degeneration. There is then a much slower decline so that at 225 days

limit of degeneration studied, the population is about 0·6 times that of the peak value. The large part played in these changes by the Schwann cells is shown by the fact that they increase about thirteenfold during the first 25 days after 225 days they fall to about half this peak value. These authors found significant differences in the rates of cellular multiplication as between tubes which had contained fibres of different sizes. This aspect of the problem was further pursued by Thomas (1948) After 25 days of degeneration the population of a somatic motor nerve had increased to nineteen times the normal while that of a sensory nerve had only increased five times After 100 days the population of the motor nerve had fallen to eleven times normal and of the sensory nerve to two and a half times normal.

Further work by Joseph (1947 1948) brought additional proof that the amount of cellular increase during the degeneration of a nerve trunk is a function of the numbers of fibres of different sizes that it contains

When re innervation takes place the multiplication and migration of Schwann cells stops as soon as the axons make contact with them (Abercrombie, Johnson and Thomas, 1949)

The investigations of Holmes and Young (1942) led to the conclusion that the preservation of the Schwann tubes in a degenerate nerve is an important determinant of regeneration. The diameter of those tubes always became smaller and especially so if the trunk remained uninnervated Sanders and Young (1944) measured the internal diameter of the Schwann tubes in the predominantly motor and in the predominantly cutaneous sensory branches of the rabbit s medial popliteal nerve. Histograms of the tube sizes were drawn showing the condition after 25 and 462 days of degeneration At 25 days many of the larger tubes are actually distended being larger in internal diameter than the largest normal fibres. Otherwise there is a general similarity between the 25 days histograms and those of the corresponding normal nerve the motor funiculi contain larger tubes than the cutaneous branches, and the fibre distribution in the motor nerve retains its bimodal character

The differences in tube sizes between motor and cutaneous nerves are still apparent after 462 days of degeneration. The average tube sizes are less than normal, as a result of shrinkage but there is also a greatly diminished proportion of large tubes and the normal bimodality of tube diameter has disappeared. Thus shrinkage is not a completely regular process for it affects some fibres more than others

(vii) *Ideal Reunion after Neurotmesis*

The best opportunity for regeneration after section is given of course, if the nerve stumps are sutured and the degree of perfection which this union attains depends largely on the precision of the operation An ideal state of affairs at a suture line is afforded by Weiss s (1944) method by which the nerve ends are joined with a well-fitting sleeve of a prepared segment of an artery *The stumps remain separated by a gap of a few millimetres* within the arterial sleeve and this becomes filled with blood The blood clots, and the fibrin thus formed fuses with the nerve stumps the erythrocytes disintegrate, leaving a spongy liquid filled fibrin mesh. The clot detaches itself from the walls of the sleeve but remains attached to the nerve stumps it thus becomes a bridge between them, and the animal s movements and the natural tensions on the nerve subject it to longitudinal stresses which tend to orientate the fibrin

elements into the long axis of the nerve Fibrinolytic enzymes destroy the finer cross-links in the network sparing the heavier longitudinal threads Thus the stumps become connected by a longitudinally disposed network along which outgrowing axons glide. The pioneer outgrowths may themselves serve as surfaces for the guidance of later streams of axoplasm, and for this reason regenerating axons are commonly found in bundles. The orderliness or otherwise of the outgrowth will be determined by the pathways available branching will be least when there is most regularity in the arrangement of these pathways and forces leading to a uniform orientation of the substratum will contribute to the regularity of the regenerative outgrowth

(viii) *Junction by Suture*

The plasma suture method of Young and Medawar (1940) enables the experimenter using small animals to reproduce the conditions found in a well conducted human operation, where the suture threads, being passed through the epineurium should not interfere with the process of reunion

The chance that an axon regenerating from a proximal Schwann tube will enter the distal part of what was formerly the same tube is extremely remote *and there is inevitably random mixing of the regenerating fibres at the suture line.*

In the sciatic nerve of the rabbit there is a latent period of nine days between primary suture and the entrance of regenerating axons into the distal tubes (Young and Medawar 1940) This time is occupied partly by retrogressive and preparatory changes in the cut ends of the proximal axons and the rest of it by *their progress across the suture line. Schwann cells from the proximal tubes flow* along the surface of the advancing axons in the tissue uniting the stumps but they never appear to advance ahead of the growing axon tips. The Schwann cell outgrowth from the distal stump however has a more direct effect in ensuring a good union

(ix) *Regeneration*

Optimal regeneration, leading to optimal functional recovery will result only when the regenerated nerve is normal in fibre composition and in the relationship of its component fibres to their end-organs and to the internuncial neurons in the central nervous system Studies of intact nerve show that among the functionally important features are the number and size distribution of the fibres, and the structure and thickness of their sheaths Regeneration is an attempt at the restitution of normality but it is a progressive process and may come to an end at any stage One of the chief contributions of the experimental work of the last ten years has been elucidation of the process of maturation in which restoration of structure and return of function go hand in hand.

Maturation must first be studied in experiments in which regeneration is taking place under the most favourable possible circumstances that is after axonotmesis.

(x) *Restoration of the Fibre Spectrum*

In any given nerve of an adult animal of one species the number of nerve fibres of each diameter is roughly constant A graph or histogram showing the population of fibres of each diameter may be called the *fibre spectrum* of the nerve. More or less complete restoration of the normal spectrum is an important element in the maturation process Sanders (1948) gives the preliminary data on the normal numbers of fibres found in the nerves under investigation in

rabbit, on their distribution in the various size groups, and of the normal values for myelin sheath thickness and axon diameter

Gutmann and Sanders (1943) showed that 200 days after axonotmesis of the rabbit's lateral popliteal nerve the size and number of the fibres in the regenerated distal *trunk are nearly normal* *The characteristic* normal bimodal distribution of fibres according to total diameter is largely restored Intermediate stages in the process were described by Sanders in 1948

Sanders later study (1948) was extended to cover a comparison of normal with regenerated nerve in respect of the sheath thickness and axon diameter of the fibres At a point 10 mm below the site of axonotmesis in the rabbit's popliteal nerve it was found that after 60 days the myelin sheaths of the newly formed fibres are approximately normal in thickness. Between 60 and 200 days the sheath gradually becomes thicker than normal in all the myelinated fibres, and the increase is maximal at 200 days. But at 300 days the measurements show a return towards the normal relationship and it may be that at some time later than 300 days complete normality is reached.

Gutmann and Sanders (1943) showed that maturation of nerve fibres after primary suture is less perfect than after axonotmesis the bimodal distribution is not restored.

It was suggested by Holmes and Young (1942) that the size of the tube into which a regenerating axon grows has a determining influence on the diameter of the fibre maturing within it. Thus if the axon of a large fibre traversed a suture line into the tube formerly occupied by a small fibre the regenerated distal segment of the fibre might never be able to achieve the full diameter of the proximal segment from which it came. If this were so it would explain the absence of the normal fibre spectrum after suture.

This possibility was investigated by Sanders and Young (1944) who made use of the fact that in the rabbit the lateral and medial popliteal nerves are of mixed function in the thigh, but divide below into branches which are predominantly motor or cutaneous the former containing larger fibres than the latter The lateral popliteal nerves were cut in the thigh on both sides and immediately sutured. Twelve months later counts were made of the number and size of the myelinated fibres in the proximal and distal trunks. Every motor branch was found to contain larger fibres than did the cutaneous branches, and comparison with normal specimens showed that after regeneration the motor and cutaneous divisions of the nerves had developed differences in fibre size similar to those in the normal Since both divisions were sutured to the same proximal stump and since random mixing could be assumed at the suture line, the explanation of these differences in the distal trunk after regeneration must be due to a peripheral factor possibly that of the diameter of the available Schwann tubes or the end-organ.

Further experiments showed that when a small proximal trunk is sutured to a large distal trunk the branching of the proximal axonal outgrowths tends to fill all *the distal tubes, and that* these branches persist to supply the increased peripheral demand. But the fibre *si es* are smaller which suggests that the regeneration of fibres of normal size depends not only on the size of the distal tube but also on the supply of axoplasm from the proximal stump Later Simpson and Young (1945) showed that only very small Schwann tubes exercise a restrictive influence for those of intermediate size can be inflated by large central fibres

Experiments involving the cross-union of nerves entail the direction of the regenerating fibres into pathways that lead them to inappropriate end-organs,

3 Peripheral Nerve Repair in Man

Most of the material consisted of damaged portions of nerve completely resected at operation A few specimens consisted of a small portion of nerve removed as an aid to diagnosis and prognosis Some muscle biopsies and a few amputated limbs, in which nerve lesions were associated with ischaemia were also examined The material which forms the basis of this report came from the Nerve Injuries Centres at Edinburgh and Oxford.

The chief aim in the study of the resected specimens, was to determine the state of cross-sections of the nerve nearest to the faces apposed at operation. The remainder of the specimen was usually examined either in longitudinal or transverse section When the nature of the lesion was such that the advisability of resection and suture was in doubt, a very small portion of nerve was sometimes taken and examined histologically (Holmes and Zachary 1946) Muscle biopsies were studied, both to determine the degree of denervation and re-innervation and also to differentiate between paralysis due to denervation and that due to ischaemia of the muscle.

A HISTOLOGICAL METHODS

Staining methods which were specific for axons and for myelin, as well as stains for other tissue elements, were applied to selected portions of the speci mens Myelin sheath staining was carried out by the Weigert Pal method on paraffin-embedded material at Oxford and on celloidin-embedded material at Edinburgh On frozen sections Anderson s (1942) modification of the Weigert Pal method was used Axis cylinders were stained by Holmes (1942, 1943 1947b) silver-on-the-slide method on paraffin-embedded material, by the Gros-Bielschowsky method on celloidin-embedded material and by Hortega s neurofibril method on frozen sections. Haemalum and eosin and Masson s trichrome were employed as general stains on paraffin-embedded material.

B REPAIR BY SUTURE

The resection of a damaged segment of nerve yields a specimen in which the condition of the two ends represents the condition of the nerve faces apposed at suture. The state of these faces is determined by the time which elapsed between injury and repair by the nature of the injury and by the extent of the resection

Since the condition of the suture line is one of the determinants of the quality of recovery an endeavour has been made to correlate the pathological observa tions on the nerve faces with the clinical assessment of recovery It is an inevitable consequence of the complexity of the processes affecting recovery that only selected cases can be included in the following account some of the conclusions are provisional and since no nerve suture is a designed experiment the results are not amenable to statistical treatment.

In the earlier stages of the investigation the attempt was made to give a histological report on the state of the suture line during the course of the nerve operation Frozen sections were cut and stained immediately after resection of the lesion This was done on the grounds that it is desirable to detect grosser abnormalities before suture is performed so that further resection may be carried out if necessary Individual bundles in a trunk may have suffered destruction of their architecture to different levels in relation to the site of maximum injury Healthy bundles may be present in one part of the nerve face

while the rest consists only of scar tissue. When a proportion of the nervous tissue is excluded from the suture line in this way by scar whether in the proximal or distal face, there is a failure of regeneration of the corresponding group of nerve fibres with an effect on function that is to some extent determined by the level of the lesion and function of the fibres so excluded However a fibrotic zone in a nerve face is usually evident to naked-eye inspection The frozen sections did not produce useful information about less gross pathological changes, and after they had been cut the remaining piece of tissue was useless for further investigation since the extreme faces had been removed The writer s conclusions are therefore based on sections cut in the laboratory in the usual way

C CONDITION OF SUTURE LINE

It may be found that one or both of the nerve faces, though not significantly scarred are composed of nervous tissue which is not in bundle form the resection has passed through the neuroma or glioma Suture of a normal proximal stump to the glioma on the distal stump can lead to good functional recovery On the other hand results of suture of a neuromatous proximal stump to a normal distal stump are seldom if ever satisfactory Many of the fibres of the proximal stump no doubt escape at the suture line and fail to reach the distal bundles. If only a small proportion of a nerve face shows a criss-cross nervous structure a good recovery may take place And when the resection has been to a level only just above the neuroma or below the glioma recovery can be entirely satisfactory in spite of oedema and disturbance of the normal architecture of the bundles.

In the study of the condition of nerve stumps it is useful to distinguish between adventitial and interfascicular abnormalities of the epineurium Fibrosis affecting only the adventitial tissue should have no ill-effects in a well-conducted suture the normal topographical relationship of the bundles is preserved and the adventitial scarring may be a positive advantage in that it makes a firm tissue in which sutures may be anchored Interfascicular abnormalities, on the other hand particularly in the form of fibrotic increase, separate the bundles and prevent accurate apposition of the nervous tissue in the stumps There is thus danger of neuroma formation at the suture line, regenerative outgrowths being blocked by the increased interfascicular tissue instead of reaching the bundles

Adventitial scarring and adhesions to adjacent muscle and fascia are almost unavoidable in any nerve wound Hence almost all proximal and distal sections will show a nerve trunk with the outer fibrous sheath considerably thickened and the areolar adipose tissue occupied by an abnormally high proportion of collagen Degenerate muscle and foreign bodies may also be found involved in the epineurium But excellent recovery can follow the suture of stumps showing gross adventitial scarring, provided that the areas of the two stumps containing the nerve bundles are carefully apposed at operation

(i) *Interfascicular Tissue and Perineurium*

Pathological change between the nerve bundles leads to all grades and combinations of abnormality in the interfascicular tissue and perineuria of the sutured faces. Serious abnormality of this kind is rarely seen in the proximal stump after a well-conducted operation. For the proximal nerve bundles containing myelinated fibres and often characterized by a glassy oedema are clearly distinguishable by inspection and touch from the connective tissue which

has a different texture It is thus relatively easy for the surgeon by trial section to find a satisfactory proximal face for suture.

In the distal trunk, however the bundles contain little or no myelin, and are thus similar in colour and texture to the interfascicular tissues If there are perineurial-epineurial adhesions the bundles will have lost the slight degree of independent mobility which allows them to be protruded by gentle squeezing of the resected segment or of the nerve trunk The distal resection is therefore often somewhat too conservative and scarring of the perineurial and inter fascicular tissue is often seen in the distal face of the specimen, representing the condition of the distal surface at the suture line. Figs. 75–78 are photographs of the distal face of the nerve in four cases illustrative of the abnormalities in

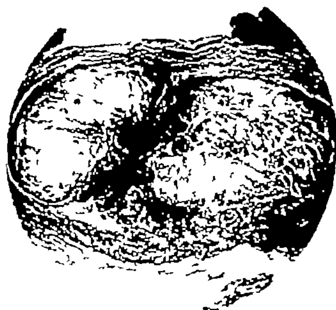


Fig 75 Transverse section of the distal face of a radial nerve divided four months previously Poor recovery The two large nerve bundles show local scarring and destruction of the perineurium. Masson's stain. 18 mm. = 1 mm.

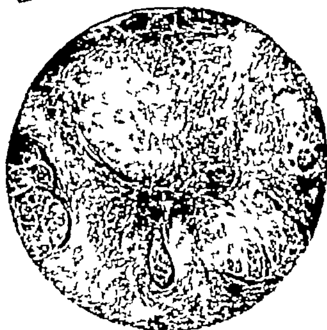


Fig. 76. Transverse section of the distal face of an ulnar nerve injured three months previously Good recovery The degree of scarring is very similar to that seen in Fig. 75 and cannot therefore be such as to prevent satisfactory recovery Masson's stain. 18 mm = 1 mm.

question They were selected on the grounds that all conditions at operation and following operation were favourable to good recovery recovery of poor quality could therefore be attributed to the condition of the distal face and the recovery observed is summarized in the legends to the figures.



FIG 77 Transverse section of the distal face of an ulnar nerve divided eight months previously Fair recovery There are many small intact bundles separated by an increased interfascicular tissue with local scarring Masson's stain 18 mm = 1 mm.



FIG. 78. Transverse section of the distal face of a median nerve injured two months previously Poor recovery The largest nerve bundle is almost completely destroyed, the outlines of its original form being traceable in the orientation of the scar tissue Masson's stain. 18 mm. = 1 mm.

(ii) *Endoneurium*

Abnormalities of the endoneurium in the proximal face at the suture line do not require separate consideration as determinants of the quality of recovery Since the Schwann tubes, if present, will be innervated, there are no progressive endoneurial changes And destruction of the tube architecture will only be found associated with perineurial and epineurial damage as described in previous

sections. To this statement the only exceptions are provided by ischaemic and *traction lesions* where endoneurial abnormality may extend above the macroscopic limits of the lesion (pp 132 and 130) Distal endoneurial changes on the other hand are great and variable and may be expected to influence recovery these changes must now be discussed

In the first few weeks after section when axon and myelin breakdown are most actively in progress, it is still possible to distinguish the tubular and trabecular elements of the endoneurium But soon after the end of the first month the *distinction becomes less clear and the surviving tubes, as recognized by their* lumina, have walls in which both elements seem involved the separate fates of the Plenk Laidlaw and Henle sheaths, of which the tubes are composed, have never been followed apart from that of the trabecular tissue.

That all the changes of Wallerian degeneration are progressive over many months, and proceed with a fairly regular tempo is clearly demonstrable in animal experiments when the nerve is aseptically divided by a sharp cut (Holmes and Young, 1942) *In human nerves also it is true that the destruction* and removal of axons and myelin, and the proliferation of Schwann cells, follow a definite temporal course. This is departed from only when the nerve metabolism is upset, as in lesions complicated by ischaemia due to vascular damage (p 134) *or in transplanted nerve (p 153) But the study of the distal faces of* resected human lesions has shown that it is much more difficult to establish the normal rate and quality of the changes in the endoneurium Part of this difficulty is no doubt due to the fact that some nerve fibres succeed in regenerat ing spontaneously into the distal tubes even after the most severe lesions, so that the appearance of the tubes is due to the changes of re innervation after a long period of degeneration.

The illustrations (Figs. 79–85) show in transverse section, a representative portion of a nerve bundle in the distal face of different suture lines. Fig. 79 shows the normal condition two months after injury Many large tubes are still visible, and those which are more collapsed have perfectly distinct lumina. *The increased endoneurial collagen often appears dense, but careful examina-*tion of the section will show clearly visible tubes (Fig. 82) The form of the endoneurial collagen is very variable and in some abnormal cases there may be patches in the nerve in which no tubes are distinguishable, as in Fig. 83 from a case in which recovery was poor

A condition not infrequently found is illustrated in Fig. 84 At first sight it appears that, five months after injury the Schwann tubes are abnormally patent, normal collapse having failed to take place. *Usually however this* state of affairs is due to some spontaneous re innervation of the distal trunk, and of course offers no hindrance to recovery after suture.

The normal condition 11 months after injury *is seen in Fig. 85* Schwann *tubes are still recognizable*, and there is no excessive increase of collagen in the endoneurium

In conclusion it *is fair to say that successful regeneration may take place* through a distal nerve face in which *the endoneurium would seem, through its* shrinkage and *fibrosis, to offer little opportunity for the reformation of new* fibres If the lumina of the Schwann tubes can be distinguished then good re covery is possible, provided that the endoneurium does not present the appearance of a solid mass of thick collagen strands. The latter state of affairs is most usually found in association *with local ischaemia (p 134) Two sections of*

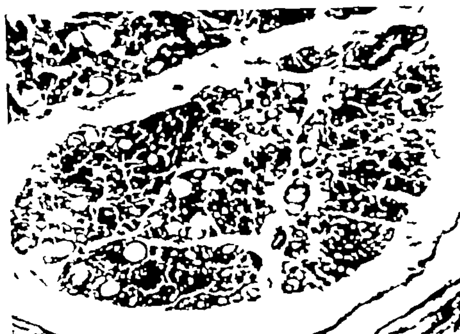


FIG. 79 Transverse section of the distal face of a median nerve injured two months previously Good recovery Masson's stain. 20 mm. = 50μ.

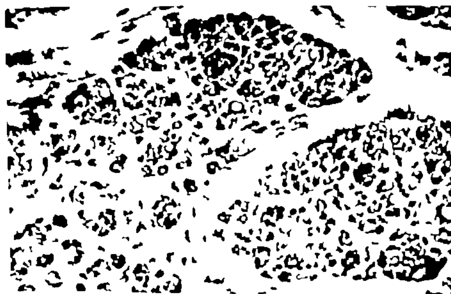


FIG 80 Transverse section of the distal face of an ulnar nerve injured three months previously Good recovery Masson's stain 20 mm = 50μ.

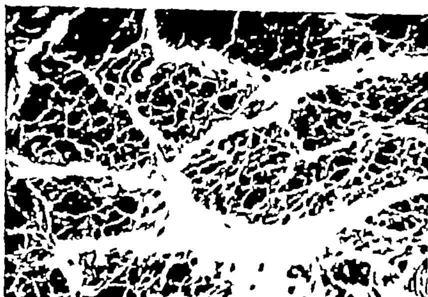


FIG 81 Transverse section of the distal face of an ulnar nerve injured three months previously Poor recovery Masson's stain. 20 mm. = 50μ.

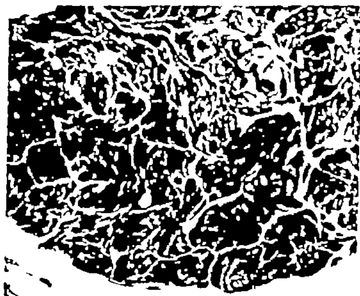


FIG 82. Transverse section of the distal face of an ulnar nerve injured six months previously Good recovery Masson's stain. 20 mm. = 50μ.

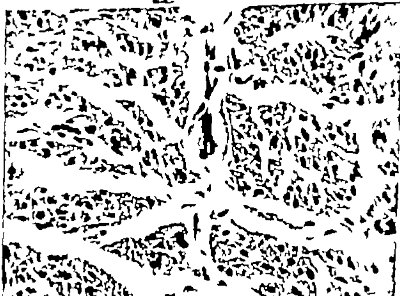


FIG. 83 Transverse section of the distal face of an ulnar nerve injured six months previously Poor recovery Masson's stain. 20 mm. = 30μ.



FIG 84 Transverse section of the distal face of an ulnar nerve injured six months previously Good recovery Masson s stain. 20 mm = 30μ.

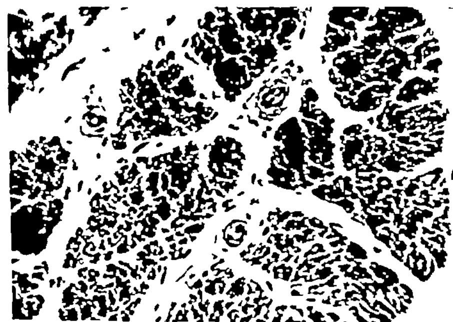


FIG 85 Transverse section of the distal face of an ulnar nerve injured eleven months previously Good recovery Masson s stain. 20 mm. = 50μ.

ischaemic nerve are presented here for comparison (Figs. 86 and 87) regeneration through such nerves is impossible Fig. 86 shows the ischaemic fibrosis of a nerve associated with Volkmann's contracture, Fig. 87 the ischaemic distal stump of a digital nerve divided in a wound which caused serious depletion of the blood supply of the fingers

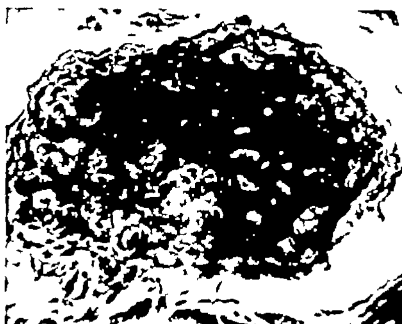


FIG. 86. Transverse section of dorsal cutaneous branch of ulnar nerve seven months after a severe vascular injury in the upper arm. Most of the Schwann tubes are replaced by dense collagen, those which remain contain macrophages. Numerous small vessels are present. *Masson's stain. 9 mm. ─40μ.*

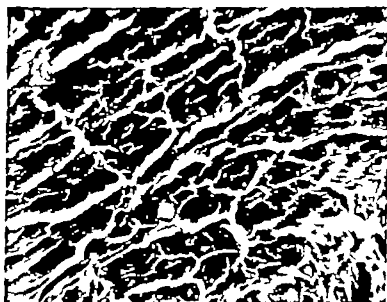


FIG 87 Transverse section of part of a nerve bundle from the distal trunk of the digital nerve on the radial side of the index finger seven months after injury of the digital nerves. No recovery after autogenous grafting. Dense collagenization of the endoneurium *Masson's stain. 14 5 mm. ─20μ.*

(iii) *Nerve Fibres*

(*a*) *Proximal face*

Experimental work has shown that regenerating fibres which fail to reach their end-organs do not return to the full diameter of the parent fibre from which they arise (p 108) In a resected lesion therefore the only normal fibres one can expect to see in the proximal sections are those which have always been intact never having degenerated at the level under investigation So it comes about that in lesions in which axonotmesis has taken place above the level of neurotmesis (as in those involving an element of traction) and in lesions causing an ascending axonotmesis consequent on inflammation (p 123) the nerve fibres in the proximal section are subnormal in diameter and myelination This state of affairs is of course, a common finding. It exists in all gradations normal fibres may be intermixed with those that are subnormal in size because they are regenerating without peripheral connexion Frequently a Weigert stained section will show normal areas in a nerve or within a bundle while other areas appear to be only sparsely innervated This does not mean, however that the uninnervated areas will not provide a satisfactory outgrowth for reunion at the suture line Since the tubes within them are continuous with tubes containing normal fibres at a proximal level no matter how much higher this may be they will become fully re-innervated from above And in fact longitudinal sections stained with silver usually show that the uninnervated areas are full of fine regenerating axons, too small for their sheaths to be visible in the myelin-stained preparations

As might be expected from this evidence and argument, it is found that the number size and myelination of the fibres in the proximal stump above a lesion uncomplicated by factors such as extensive ischaemia have no effect on the quality of recovery obtained This fact has been repeatedly demonstrated No doubt there is an effect on the rate of recovery and axonotmesis high above the level of injury will cause an apparently unduly slow rate of regeneration But the time variable acting in this way is usually covered by the extremely broad estimate of the delay at the suture line which is used in predicting the time of onset of the first signs of functional return (p 16)

A considerable degree of endoneurial oedema is commonly found in proximal sections and it manifests itself to the naked eye as a glassiness of the nerve bundle which the surgeon soon comes to recognize. It is shown in sections by a wide spacing of single myelinated fibres or of groups of fibres The tubular endoneurium remains intact and the oedema results in a dispersion of the fibrils of the trabecular endoneurium. It has not been possible to correlate the occurrence of this oedema with any particular type or severity of injury nor is it found only within a certain period of time after wounding. Its persistence over many months indicates that it is not a simple inflammatory oedema and there have been no signs that the oedematous zone becomes occupied by fibrous tissue It is tempting to accept the view of Weiss that it is a consequence of the damming up at the site of injury of a tissue fluid specific to the endoneurium which normally flows regularly in a proximo-distal direction in intact nerves

There is no evidence that this oedema in the proximal face has any adverse affect on the quality of recovery It causes a general distension of the nerve trunk, so that an oedematous proximal stump is a good deal larger in diameter than the distal stump to which it must be sutured quite apart from the natural shrinkage of the latter This possible source of poor union must be overcome, if possible, by careful suture.

The oedema gradually becomes less marked in sections made at intervals up the proximal stump above the level at which normal nerve architecture is restored But to obtain a nerve face devoid of oedema by drastic resection leaving a larger gap to be closed is more undesirable than that of suture of an oedematous stump.

(*b*) *Distal face*

The presence of nerve fibres in the distal face at the suture line is not a factor which can have any direct influence on the course of regeneration, for the fibres will have been surgically divided from their cell bodies and will degenerate after suture. Indirectly it may have a favourable influence in that re-innervation during the interval between injury and operation may have done something to retard atrophic changes in the distal nerve and perhaps in a few end-organs.

The pathologist may however be asked for his comments when the distal face is innervated for correlation with pre-operative clinical findings, and for advice as to whether conservative treatment would have been more proper than resection and suture

There are few lesions so severe even when neurotmesis is complete, that no regenerating axons succeed in reaching the distal nerve. Even when these fibres are so small in diameter as to be undetectable in myelin-stained preparations, longitudinal sections of the distal part of the lesion stained by a silver method, will show a few fine axons coursing along the Schwann tubes. A less severe lesion will allow of the passage of more fibres and a greater increase in their diameter In such a case the distal section if myelin-stained will show numerous small myelinated fibres, scattered amongst apparently uninnervated tubes (Fig. 88) The degree of re innervation illustrated in this figure, if found in the distal face more than a month after suture is insufficient to indicate that conservative treatment would have led to good recovery resection and suture were justified

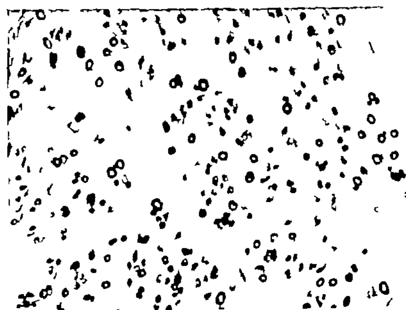


FIG 88 Transverse section of a biopsy from the trunk of the radial nerve 8 cm. below the upper level of the lesion inflicted six months previously Some spontaneous regeneration is in progress but the fibres are still small. Myelin stain + carmine. 10 5 mm. = 20 μ.

A more ample re-innervation of a distal face is seen in a myelin stained preparation, in Fig. 89 and in axon stained longitudinal section in Fig. 90 In such a case spontaneous regeneration is well in progress the tubes are abundantly re-innervated and increase in diameter and myelination is proceeding. A distal face in this condition indicates that the lesion was either one of neurotmesis with good reunion or of axonotmesis, and a better quality of recovery might have followed conservative treatment.

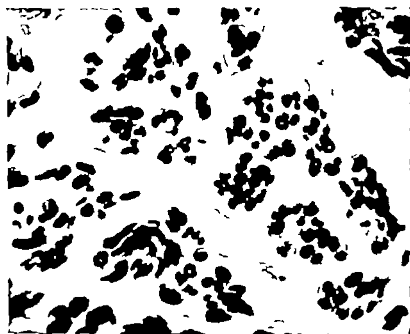


FIG. 89 Transverse section of a biopsy taken 1 cm. below the site of a primary suture of a median nerve performed 13 months previously Abundant re-innervation Myelin stain+carmine. 10·5 mm = 20μ.



FIG. 90 Longitudinal section of a biopsy taken at a point distal to a pressure lesion of the posterior interosseus nerve inflicted ten months previously Re innervation is taking place but the diameter of the axons is subnormal. Axon stain. 11 mm. = 20μ.

An appearance such as that shown in Fig. 91 with a nerve bundle partly myelinated partly unmyelinated, indicates a mixed lesion with local variations in severity It is difficult, in such a case, to decide whether the advantages of conservative treatment would have outweighed those of *resection and suture*.

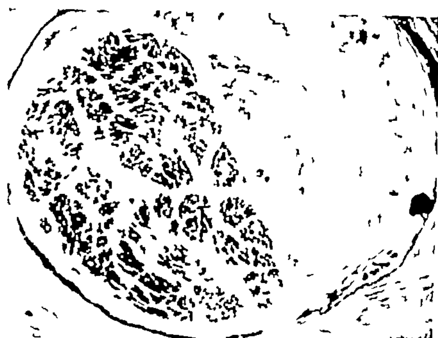


FIG 91 The same case as in Fig. 89 Transverse section of a whole bundle of the median nerve 1 cm. below site of suture. Re-innervation is much further advanced in one half of the bundle than in the other Myelin stain + carmine. 10 mm. = 100µ.

(iv) *Primary Suture*

Although it has long been believed that primary suture is the ideal method of repair it has not been sufficiently recognized that this ideal procedure requires ideal conditions These though readily attainable in the laboratory are rarely present in clinical practice. After comparing the results of primary with those of early secondary suture, Zachary and Holmes (1946) concluded that the secondary operation gave more consistently satisfactory results a similar view was subsequently expressed by Spurling and Woodhall (1946) There are a number of technical reasons for preferring early secondary suture Adequate mobilization of the nerve stumps can be more safely performed the suture may often be sited at a point away from the zone of greatest damage to the neighbouring tissues and the post traumatic thickening of the epineurium provides excellent material for holding stitches. But the strongest argument is based on the appearances of the zone of primary suture found in cases where a secondary operation has been performed either because recovery was absent at the expected time or (as in the later experience at the Oxford Centre) because surgeons had come to distrust primary suture to such an extent as to regard it as a clear indication for secondary repair In all the specimens examined the stumps showed more or less pronounced fibrosis usually more extensive distal to the suture line than proximal to it. The total longitudinal extent of the zone of intraneural scar was as much as 4 cm in one case and in all it was sufficient completely to preclude satisfactory regeneration.

There are two possible explanations and it seems necessary to invoke both. Firstly the violence of the injury even when it was thought to have been inflicted

by a sharp object such as a piece of glass may have produced intraneural damage on either side of the line of severance. Secondly even in the absence of such disruptive violence, the nerve ends may have been damaged as a result of acute ischaemia caused by severance of the intraneural vessels this possibility is supported by the finding of more extensive damage distally for the proximal stump would still be nourished to some extent by its distally directed longitudinal blood supply Neither type of damage would be clearly recognizable at the time of primary suture both would be manifest later by the consequent intraneural scarring. This is the chief reason for recommending the abandonment of primary suture even for nerve injuries due to apparently clean incised wounds.

D COMPLICATIONS

(i) *Pyogenic Infection*

In contrast to experience in the First World War (Platt and Bristow 1924) pyogenic infection was an infrequent complication of nerve wounds. In the few cases in which it was present there was seldom evidence in stumps which were subsequently removed of the interstitial fibrosis, especially the endoneurial fibrosis proximal to the injury mentioned by these authors. Indeed there was little or no damage that could be definitely ascribed to infection

(ii) *Ill Effects of Sulphonamides*

Sulphanilamide has been shown experimentally (Holmes and Medawar 1942) to cause axonotmesis if applied in high concentrations alongside a nerve. Ill effects associated with sulphanilamide treatment were seen in one case The patient cut the anterior aspect of the right forearm with corrugated iron. A few hours later the wound was explored. The ulnar nerve was found divided it was stitched and sulphanilamide was put into the wound. Six and a half months later there was no clinical recovery and secondary nerve suture was done. Examination of the excised specimen revealed that the two nerve stumps had been sutured close together neuroma formation being small, but accompanied by the presence of much collagen Unusually marked endoneurial fibrosis was also present in the poorly innervated distal stump Suture material was seen only at the periphery of the junction zone

(iii) *Foreign Bodies and Suture Materials*

Cloth fibres metallic fragments bony fragments and particles of rock had entered some nerves at the time of injury and the tissue reaction subsequent to suture with silk catgut or linen thread was often seen

Around particles of metal which were presumably sterile when they entered the body was content to erect a relatively thin fibrous wall Small particles of crystalline, doubly refractile rock (Figs. 92 and 93) were found engulfed by multi nucleated giant cells accompanied by a slight exudate of lymphocytes and endothelioid cells and were walled off by a well-marked zone of fibrous tissue Generalized fibrosis was not present.

In many cases, without any history of previous suture the removed segment of nerve contained grouped or separate animal or vegetable fibres coming presumably from clothing. Most of them were rather ovoid varying in calibre smooth surfaced (Fig. 94) and composed of a homogeneous anisotropic substance (Fig. 95) Some were colourless some brownish and some blue black, and since they lacked the surface irregularities of wool they were considered to be cotton These fibres were associated with a pronounced reaction on the part of lymphocytes and multi nucleated foreign body giant cells. Fibrous tissue



FIG 92. Foreign body Particles of rock in a nerve injured seven and a half months previously The dark particles are separated from the rest of the tissue by a thick fibrous wall H & E. 1 cm. = 100μ.

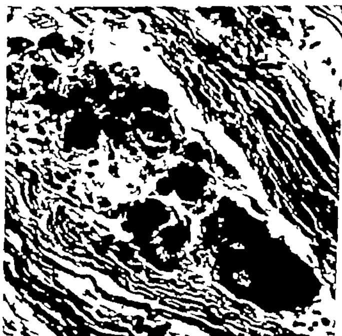


FIG. 93 Higher power view of previous section showing rock particles engulfed by multi-nucleated giant cells and surrounded by endothelioid cells. H & E. 16 mm. = 50μ.

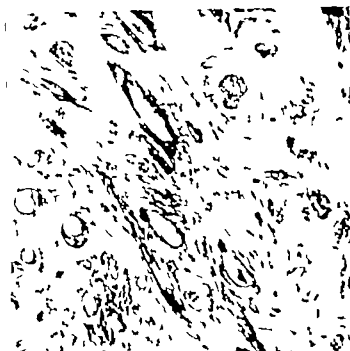


FIG. 94 Scar tissue between neuroma and glioma of a median nerve injured by a bullet four months previously. Cotton fibres (presumably from clothing) are present, many engulfed by multi-nucleated giant cells; there is well marked fibrosis. H & E. 12 mm. — 100μ.

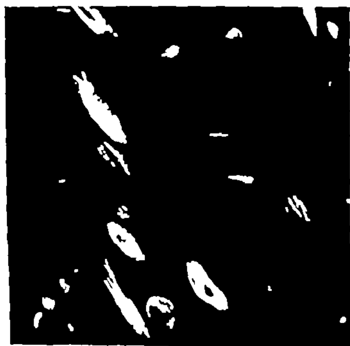


FIG. 95 The same field as Fig. 94: polarized light reveals the anisotropic cotton fibres. 12 mm. — 100μ.

formation was not usually marked when the fibres lay within the neuroma or glioma, but was more noticeable when they lay in the epineurium or in some situation outside the nervous tissue (Fig. 94) The opinion formed was that cloth fibres were not a source of much fibrosis

In one neuroma, examined four months after injury fragments of dead bone and of muscle were present (Fig. 96) They were surrounded by dense fibrosis and had provoked a well marked lymphocytic and giant-cell reaction.



FIG. 96. Distal glioma of median nerve injured by bullet four months previously In the upper part of the picture are cloth fibres In the middle are particles of dead bone and in the lower part necrotic muscle. All these foreign bodies are surrounded by thick walls of fibrous tissue. H. & E. 2 cm. = 1 mm.

Of suture materials silk catgut and linen thread were seen, all having been present for more than three months Thus the cellular reaction was seen in its later stages The general impression gained was that suture material caused only local fibrous tissue formation After three months, plain linen thread caused least fibrosis, and silk either plain (Fig. 97) black (Figs. 98 and 99) or waxed (Figs. 100 and 101) caused more than catgut (Fig 102) The position of the suture in relation to the nerve ends appeared to be a more important factor in impeding nerve fibre outgrowth than the fibrosis provoked by the material. Absorption of suture material occurred only with catgut which was almost entirely removed by four months Linen thread was almost un affected when seen at three months, black silk was relatively intact at three months, plain silk at eight months waxed silk at ten months. At four months catgut had left little cellular reaction and the unabsorbed linen thread was equally innocuous. In each case only an occasional phagocytic giant cell was present. This finding contrasts with the florid cellular reaction to chromic catgut during the first two months which was found in experimental animals by Sargent and Greenfield (1919) and Guttmann (1943) The first two authors and the writers agree, however in commending plain linen thread. Silk thread whether plain dyed black or waxed, in the human subject caused a considerable

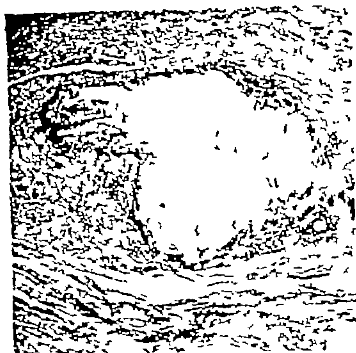


FIG. 97 Neuroma of radial nerve cut by knife stab and sutured with plain silk eight months previously There is a lymphocytic, endotheliold cell and giant-cell reaction and well-marked fibrosis. H & E. 22 mm.=0 5 mm.



FIG. 98. Neuroma of ulnar nerve injured by a bullet and sutured with black silk three months previously Note the lymphocytic and giant-cell reaction and the well-marked encapsulation by fibrous tissue of the silk threads which are the thick black objects on the right of the picture H & E. 18 mm.=0 2 mm.



FIG. 99 Neuroma of ulnar nerve cut and sutured with black silk three years previously *The cellular reaction is now inactive but a thick capsule of fibrous tissue* separates the unabsorbed silk from the adjacent myelinated nerve fibres. Myelin stain. 13 5 mm. = 0·2 mm.



FIG 100 Neuroma of a median nerve cut by glass and sutured with waxed silk ten months previously Many silk fibres (*black*) lie embedded in homogeneous waxy material (*top half of picture*). Around this mass is a well-marked cellular reaction. H & E 15 mm. = 0·2 mm.

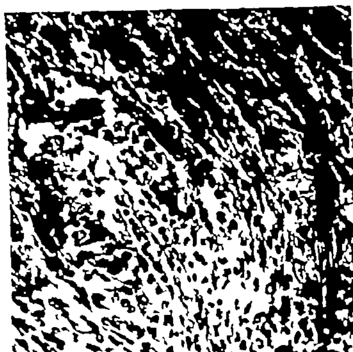


FIG 101 Higher power view of part of previous picture. Some sutures are embedded in wax (*top of picture*). Other sutures (*one in lower right of picture*) lie amongst lymphocytic and endothelioid cell reaction. 16 mm. = 50μ.

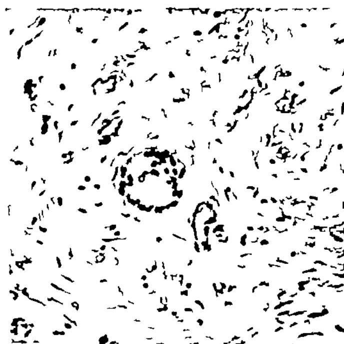


FIG 102. Neuroma of a lateral popliteal nerve injured by a bullet and sutured with catgut four and a half months previously. Most of the catgut has been absorbed but a strand lies within a multinucleated giant cell. Fibrous tissue increase is slight. H & E. 16 mm. = 50 μ.

and persistent lymphocytic, endothelioid and phagocytic giant-cell reaction for many months at least 10 months in the case of waxed silk. Sunderland and Smith (1950) found that fine, plain catgut, white silk and human hair were the most suitable materials for nerve suture however they did not investigate the properties of linen thread

E TRACTION LESIONS

Violent longitudinal stretching of a nerve trunk, causing rupture of vessels and nerve fibres and tearing of the stroma, must contribute to the damage caused by many forms of trauma. But there are certain nerve injuries, usually arising in particular anatomical situations where the whole lesion can be attributed to nothing other than longitudinal stretching of the nerve trunk concerned. Experimental investigation of the consequences of nerve stretching throws light directly on the aetiology of such lesions, and indirectly on lesions in which traction has been contributory

Denny Brown and Doherty's (1945) studies on the lateral popliteal nerve of the cat showed that it could be stretched to give as much as 100 per cent increase in length without causing rupture of the nerve trunk as a whole and often without producing pathological changes in the nerve fibres. Greater stretching was liable to cause rupture, which took the form of a longitudinal split in the perineurium through which the nerve fibres herniated Such an injury resulted in an immediate complete paralysis. Some weeks later function had completely returned, but at the site of injury there was a large fusiform neuroma. This swelling was due to oedema, and to some extent to a true neuroma formation due to the rupture of those nerve fibres which had lain close to the tear in the perineurium More severe damage, causing a greater degree of herniation led to destruction of the Schwann tubes at the site of injury even though it did not lead to gross interruption of the continuity of the nerve. The zone of damage came to be occupied with scar tissue, so that the lesion amounted to one of complete neurotmesis without possibility of reunion, but the preservation of anatomical continuity

The authors attribute many of these pathological changes to injury of the vasa nervorum causing patchy oedema and haemorrhage. They noted abnormally rapid dissolution of axons and myelin where fibres were divided and point out the similarity to the changes in the degeneration caused by compression.

Acute stretching of a nerve is commonly seen in traction injuries of the brachial plexus and of the lateral popliteal nerve (Highet and Holmes, 1943). It is perhaps less obvious that damage due to acute stretching is also present in injury due to missiles, when the bullet passes either close to the nerve or through it but Puckett *et al* (1946) have shown experimentally that momentary displacement and therefore stretching of a nerve accompany the near passage of a bullet, and it must therefore also be present when the missile touches or pierces the nerve. Thus in nerve injuries associated with bullet wounds the damaging effects of stretching cannot be ignored In nerves from human cadavers, Liu, Benda and Lewey (1948) showed experimentally that after elongation not exceeding 4 2 per cent there was subsequent elastic recovery of the initial length of the nerve above 6 per cent the axons and the myelin ruptured, all fibres were ruptured by 10 per cent elongation, and above 20 per cent elongated tears of the endoneurium occurred, with haemorrhages from endoneurial and perineurial vessels. Above 22 per cent there were *longitudinal* tears of the perineurium with herniation of the overstretched nerve fibres.

Many of the nerve lesions due to bullet wounds in man are similar in naked eye and microscopical appearances to these experimental lesions.

Another feature mentioned by the experimental workers which is well recognized clinically is that damage to the nerve is not restricted to the point of maximum stretching but extends widely At the point of greatest damage the tear may involve nerve fibres endoneurium and perineurium while, at points far above and below it the perineurium may be intact but, within it nerve fibres and endoneurial tubes may be torn

One case of traction injury was of particular interest in that it was an example of axonotmesis

Seven months before operation a man of 39 stumbled over a box and fell, his leg being externally rotated he experienced severe pain in the popliteal region, radiating to the foot, and immediate loss of power in the leg. One month before operation complete lateral popliteal paralysis was still present. The lateral popliteal nerve was found to be hard and apparently fibrosed over a length of 7 5 cm. from the point of division of the sciatic nerve to a level 2 5 cm above the fibular neck. In the lower third of the popliteal space the nerve was surrounded by dense scar tissue. The excised portion of nerve, about 22 mm. long, was a tapering piece of tissue without any end-bulb formation Histologically there was no evidence of neuroma formation (Fig. 103) the epineurium was thickened by fibrous tissue, the perineurium





FIGS. 103 (*top*) and 104 (*bottom*). Longitudinal section of a lateral popliteal nerve injured by traction seven months previously The bundles of endoneurial tubes run intact through the specimen but are not all running in the plane of the section. Myelin stain 1 cm. = 20 mm.

Longitudinal section of same nerve showing at least three axonal outgrowths in an endoneurial tube, which also contains proliferated Schwann cells. Gros-Bielschowsky stain. 10 mm. = 20μ.

was intact and the endoneurial tubes, though often separated by oedema, ran without visible interruption from the proximal to the distal end of the specimen. Proximally the nerve bundles were fairly well-filled with fine nerve fibres, some of which were myelinated focal cellular fibrous thickening was present in the perineurium the endoneurial tubes often contained more Schwann cells than normal and several nerve fibres were frequently seen in one endoneurial tube. Thus even at this level the nerve was regenerating and the section had been made distal to the proximal level of initial degeneration The fine nerve fibres ran along the length of the specimen, often in leashes of two or three or possibly more, within endoneurial tubes that were filled with Schwann cells (Fig 104). The number and diameter of the nerve fibres decreased in traversing the length of the specimen, so that at the distal end, which was still oedematous, there were fewer and finer fibres within the endoneurial tubes.

In eight cases of traction injury of the lateral popliteal nerve Highet and Holmes (1943) found extensive longitudinal damage, with evidence of complete degeneration of axons and myelin throughout the resected portions of nerve, even for 20 cm. proximal to the head of the fibula They found, however considerable variation in the degree of disruption. In one case only the axons and myelin were torn in three the endoneurial tubes had been ruptured at different levels and the perineurium had been torn in four cases there had been complete rupture of the nerve. Fibrous thickening of endoneurium, perineurium and epineurium were commonly present and many arteries in the nerves showed intimal fibrosis, in some cases with almost complete obliteration of the lumen. Oedema and perivascular lymphocytic infiltrations were frequently seen. When some continuity of the nerve was present, axons had reached the distal portion but they were slender and thinly myelinated

A standard procedure for the surgical repair of extensive gaps in damaged nerves consisted formerly of flexing an appropriate joint to a very considerable degree, suturing the nerve after mobilization and then slowly extending the joint. This procedure was adopted in some of Highet and Holmes cases of injury to the lateral popliteal nerve. There was no evidence of recovery in four out of five cases and when at a later date the region of suture was explored, histological examination showed changes similar to but even more severe than those seen in the initial lesion. The practical significance of this work in the choice of autogenous grafting as a method of repairing large gaps is elaborated in Chapter IX. Highet and Sanders (1943) investigated this post-operative stretching experimentally in the dog. They found extensive retrograde degeneration and diffuse replacement by collagen in the portion proximal to the suture, together with oedema collagen replacement and haemorrhages from small blood vessels in the distal trunk. They did not see intimal fibrosis or thrombosis of arteries.

F ISCHAEMIC LESIONS

The pathological changes consequent on injury to nerves by compression, cooling and other agencies have been held by some authors to be the direct result of interference with the blood supply But the unequivocal demonstration of the pathology of neural ischaemia can come only from the study of the results of uncomplicated obstruction of blood vessels. A precise correlation should be possible between the site and degree of the ischaemia produced and the consequent pathological changes, though such investigations have proved more difficult than might have been expected.

In 1942 Adams surveyed existing knowledge of the gross and fine anatomy of the vasa nervorum, and proceeded (1943) to an investigation of the effects of interference with their function His results, together with some new work along similar lines are admirably summarized by Durward (1948) A peripheral nerve receives nutrient branches from adjacent arteries which arise at all levels and

show considerable anatomical variation These regional sources of supply enter the epineurium and form branches often both ascending and descending, which make up the capillary bed outside the bundles This capillary system is made up of anastomoses continuous throughout the length of the nerve. The regional nutrient arteries provide the blood that is coursing through the plexus but no single nutrient artery furnishes the sole blood supply of any segment of nerve It seems that the pre-capillary branches found in the epineurium are also anastomotic. These conclusions on the internal architecture of the vascular system of peripheral nerve were based to a considerable extent on the results of experiments primarily designed to study the effects of extensive surgical mobiliza tion on the nutrition of nerve trunks. It was found in rabbits for example, that complete mobilization of the sciatic nerve throughout the thigh resulted in no significant disturbances in the function of the nerve and no pathological change There is thus experimental support for the assumption on which surgeons have long acted with success A small amount of local pathological change was found if the longitudinal vessels in the epineurium were cut at the same time as the nutrient arteries were divided

This non regional character of the blood supply is one of the chief difficulties in the way of a precise study of ischaemic neuropathy Further difficulty arises from the unpredictability of the circumstances in which collateral sources of supply are opened up and of the conditions under which vascular spasm and throm bosis may spread from the site of an experimental occlusion These difficulties are well shown in the results of an attempt to study the effect of severe ischaemia on the nerves of the rabbit s hind leg (Highet and Holmes, unpublished work)

In four animals the common iliac and common femoral arteries were ligated on the left side. Eight weeks later the first animal showed analgesia over the whole of the sole and dorsum of the left foot the second showed analgesia extending up both aspects of the leg. In the third and fourth animals analgesia extended up both aspects of the leg and included the distal half of the sole and dorsum of the foot. All showed motor loss in that the toe-spreading reaction was absent. The fourth animal showed also a well-developed muscular contracture the ankle and toes were acutely plantarflexed, and there was con siderable wasting. The state of the arterial circulation in both normal and operated limbs was examined in each animal by contrast radiography The collateral circulation in the operated limbs was so profuse that the ligated vessels were filled between and beyond the ligatures there were however considerable variations in the extent to which the circulation was re-established in different regions in each case thus for example the animal with the severe muscular contracture showed well-filled distal vessels but local deficiencies of arterial supply in the region of the affected flexor muscles. Autopsy specimens of the limb nerves showed similar variation in the extent and nature of the ischaemic change most of those taken distal to the mid thigh had undergone Wallerian degeneration, but re innervation was in progress and had reached varying degrees of completeness There was little evidence of pathological change other than degeneration except in some plantar nerves which showed endoneurial fibrosis

These few experiments show some of the difficulties which arise from attempts to control the site and degree of nerve ischaemia. Many of the nerve specimens showed hypertrophy and proliferation of the vessels of the interfascicular longitudinal pathway and of the pre-capillary vessels of the epineurium, and these enlarged and new-formed vessels usually seemed to contain normal blood

The experimental studies of neural ischaemia thus lead to the following conclusions. Destruction of the nutrient arteries as they approach the nerve produces no significant effect, nor does it impede regeneration (Bacsich and Wyburn, 1945). Damage to the epineural vessels has a local effect, determined in its extent by the degree to which the longitudinal blood flow is impeded. The pathology of these changes is identical with that described as a consequence of pressure. The progressive pathological changes resulting from more severe degrees of impairment of the circulation have not yet received adequate experimental study

Several specimens of injured nerves were examined from patients in whom the nearby large artery and sometimes the accompanying veins had also been damaged. At the time of examination, some months after the injury the vessels were partly or completely filled with organized, sometimes recanalized, thrombus. In spite of this indication that, initially complete or almost complete vascular occlusion had been present, there was no evidence that the histological course of nerve regeneration had thereby been influenced. The proximal and distal faces and the neuroma were similar to those seen in cases where no damage to neighbouring vessels had been found.

However in some cases, in which the main artery to a limb was occluded resulting in a degree of ischaemia sufficient to cause death of muscle and Volkmann's contracture, the ischaemia also caused histological changes in the nerves, which varied presumably according to the degree of ischaemia. In nerves examined four months to two years afterwards, there was perhaps only degeneration of axons and myelin, similar to Wallerian degeneration, or these changes were sometimes associated with marked increase of endoneural collagen and narrowing of the endoneural tubes. In more severely affected nerves fibrosis was often more widespread the whole nerve even being replaced by fibrous tissue. Regeneration through such tissue was bound to be slow and poor In regions where the ischaemia had been very severe from the onset, the nerve underwent coagulative necrosis, with preservation of its outline but loss of its nuclei, similar to that seen in ischaemic muscle (Holmes, Highet and Seddon, 1944)

PART II. HISTOPATHOLOGY OF NERVE GRAFTS

by F K. SANDERS

1 Value of Nerve Grafts as Determined by Animal Experiment

THE operation of nerve grafting includes all procedures in which a bridge of nervous tissue is inserted between the cut stumps. Nerve grafts may be *autografts* (pieces of nerve from the same individual) *homografts* (pieces of nerve from another individual of the same species), or *heterografts* (pieces of nerve from an individual of a different species) Grafts of all three types have been used either when fresh, or after such treatment as predegeneration, storage in various media, or killing by fixation in alcohol or formalin.

Recovery of both sensory and motor function in animals has been reported by various workers following all the above types of graft (see Sanders 1942, for review of literature) but considerable divergences exist in some cases between the results of animal experiments and operations on man

However experimental studies of nerve grafting are usually carried out under conditions which are far more favourable than those met with clinically The graft can be placed in a gap created by the resection of a segment of nerve with a minimum of trauma and under aseptic conditions In human cases grafts are inserted at a secondary operation performed long after an injury of exceptional severity where pathological changes may be extensive, the operation being reserved for cases in which end to-end suture is impossible. Thus it is not surprising that procedures which are successful in animal experiments frequently fail in man The value of animal experiment is that it enables the experimenter to compare different procedures under standard conditions and to reject those which are definitely inferior reserving the more successful methods for the severe test afforded by the human situation The main defect of the earlier literature is that it contains very few reports of experiments in which the results of different types of graft have been compared by means of standard tests. The account of nerve grafts given below is based mainly on the work of Gutmann Sanders, Weiss Young, and of others, in which grafts of different kinds were used to fill gaps of the same length at the same level in the lateral popliteal nerve of the rabbit, and the results compared by standard criteria Four types of test were applied (a) measurement of the rate at which pain fibres grew through grafts of various kinds (Gutmann Guttmann Medawar and Young, 1942 Sanders and Young, 1942) (b) comparison, for such grafts, of the time of onset and quality of recovery of the function of reflex spreading of the toes, which in the rabbit, is performed only by muscles innervated by the lateral popliteal nerve (c) measurement of the return of sensibility to pinprick on the dorsum of the foot within the autonomous zone supplied by the lateral popliteal nerve (d) comparison of the histological appearances of different kinds of graft at comparable intervals after their insertion The functional results obtained were compared on the one hand with the results of suture, and on the other with the results of the unaided union of stumps across nerve gaps of the same extent, these being chosen as procedures with the best and worst prognosis following nerve severance

Eight out of eight cases of suture studied by Gutmann and Sanders (1942) recovered toe-spreading in 56 to 85 days (Fig. 105) spreading of a little less than the normal amplitude being finally achieved Only two out of 14 unaided unions recovered toe-spreading of minimal amplitude in 117 and 162 days and there was no subsequent improvement. Sensory recovery on the dorsum of the foot was complete after three sutures at 124 (twice) and 159 days sensory recovery was absent in all unaided unions studied

A AUTOGRAFTS

Small thin autografts in experimental animals were able to survive degenerate and conduct new fibres across the gap in the nerve into which they had been inserted New nerve fibres grew through 2 cm autografts in the lateral popliteal nerve of the rabbit at approximately 2 mm a day only a little more slowly than the 3 5 mm. a day at which they grew through the peripheral stump below a point at which the nerve had been severed and reunited by immediate suture (Sanders and Young, 1942) The latent period before fibres first appeared

within such a graft—the time which they took to cross the proximal junction—was about nine days the corresponding latent period for a nerve suture was seven days.

Recovery of reflex motor function and of cutaneous sensibility also followed the experimental use of autografts Reflex spreading of the toes first reappeared in eight out of 10 cases 51 to 98 days after inserting 2 cm. autografts into the lateral popliteal nerve of the rabbit (Fig. 105) The full amplitude of toe-spreading characteristic of the normal animal was never restored, although the rate of

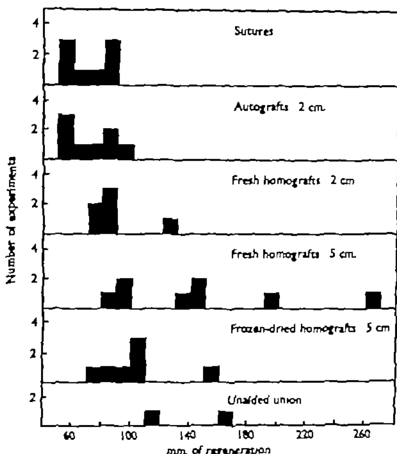


FIG. 105 Histograms to show the times of onset of motor recovery (spreading reflex) after end-to-end suture, various nerve grafts, and the unaided union of stumps. Grouped by ten-day intervals. Data from Gutmann and Sanders (1942) and Sanders (unpublished).

improvement of spreading followed its onset, and the final grade of recovery attained, was of the same order as that following suture. Sensory recovery after autografting was less frequent and more delayed as compared with suture.

Histological examination of small experimental autografts showed that degeneration and re innervation proceeded almost exactly as in a normal distal stump Proliferation of Schwann nuclei and break up of the myelin proceeded actively and the graft became populated by macrophages which removed the remains of axons and myelin, although all these processes took place more slowly than in a normal distal stump (Figs 106 and 107) However autografts examined in the terminal stages of regeneration resembled normal distal stumps very closely



FIG 106. Part of 2 cm. autograft 25 days after insertion showing resemblance to normal distal stump Note Schwann bands and spaces filled with macrophages.

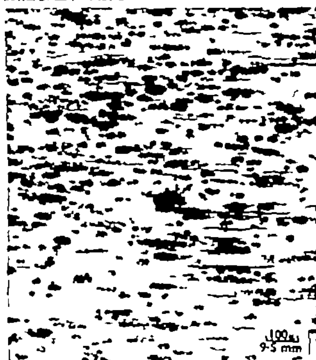
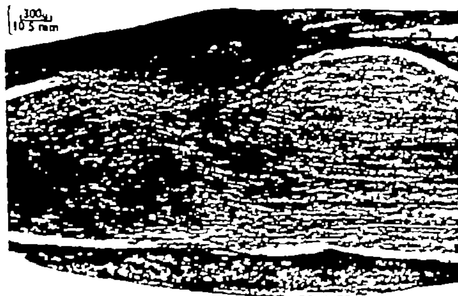


FIG 107 Autograft after 25 days showing normal disintegration but slow removal of myelin. New fibres in the graft are already becoming myelinated.



Union of autografts with stumps took place in a manner indistinguishable from that which follows nerve suture (Fig 108) The lower junction in particular was made by Schwann cells and fibroblasts (originating, presumably from both the graft and the host nerve) well before the arrival of axons from the proximal stump The union was already well made 15 days after grafting (Fig 109) so that the fear expressed by Davis and Cleveland (1934) of the delay and obstruction of new fibre growth on account of fibrosis at the lower junction seems to have little experimental foundation Occasional fibrosis occurs in autografts but is not restricted to the lower junction.

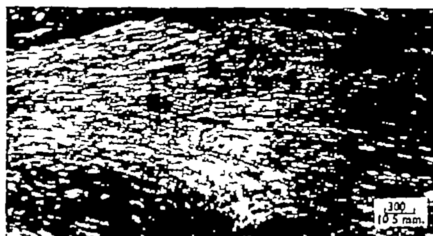


FIG. 109 Distal junction of an autograft after 15 days graft to the left. A smooth union has been made although no nerve fibres have yet arrived.

When new fibres reached the lower junction they crossed it with very little delay (Sanders and Young, 1942) In order to confirm this for long grafts two grafts 5 cm long were used, and the animals examined at a time when by calculation from the results of 2 cm grafts, fibres should have reached the lower junction In both cases this had indeed occurred, and fibres had travelled some way into the distal stump In addition the histology of the distal junction of these long grafts, in which any fibrosis should have been specially marked, showed no greater degree of collagenization or obstruction of fibres than had occurred with the standard 2 cm. grafts.

Myelination of the new fibres proceeded in autografts almost as rapidly and completely as in a normal distal stump At 200 days after grafting many fibres of various sizes were present, but the largest were smaller and less numerous than in the proximal stump There was, however little difference between autografts and comparable levels in normal distal stumps in this respect, since neither showed a group of large fibres in the fibre-size histogram such as is seen regularly in normal mixed nerves.

Grafts of predegenerated nerve Tello (1907) and Cajal (1928) both suggested that quicker regeneration would be obtained if autografts were made not with fresh nerve, but with distal stumps which had been allowed to degenerate for 8 to 15 days before implantation. However Huber (1920) found that while autografts degenerated for 20 to 30 days were as effective as fresh autografts, they were no better Similar results were obtained by Bentley and Hill (1936) and Bunnell and Boyes (1939) although Duel (1934) had claimed that fibres grew

through such grafts one and a half times as fast as through fresh ones Sanders and Young (1942) found no difference in the rate at which new fibres grew through fresh grafts compared with those which had been degenerated for 6 to 9 14 to 16 or 25 to 28 days There was evidence, however that the latent period before fibres first appeared within the graft was shorter in the case of predegenerated grafts (6 9 as compared with 9 2 days) Abercrombie and Johnson (1942) showed that the period 15 to 25 days after severance of a nerve is the one in which the Schwann cells of the distal stump show the greatest tendency to wander out from it. By reason of this power predegenerated grafts may make somewhat better junctions than fresh grafts This would account for the greater rapidity with which new fibres appeared within them and the frequent absence of bulbs and adhesions at the junctions between such grafts and the host nerve.

Histologically predegenerate nerve autografts showed little difference from fresh autografts, and the experimental evidence suggests that any advantage which such grafts may possess does not lie in their more rapid penetration by new fibres. Predegenerate nerve however has a firmer consistency than fresh and is easier to handle. For mechanical reasons predegenerate grafts may be superior to fresh grafts in man in situations such as the facial canal and by reason of their resistance to the transient ischaemia which follows transplantation predegenerated autografts may be definitely superior to fresh grafts when large transplants are used (Seddon 1947 b)

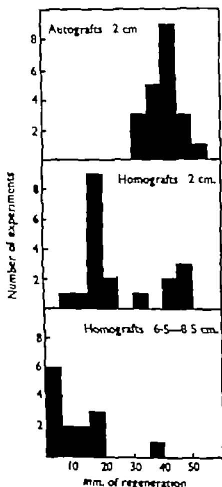


FIG. 110 Histograms to show the frequency with which nerve fibre outgrowths of each distance were obtained through (a) 2 cm. autografts, and (b) 2 cm. homografts 25 days after insertion and (c) 6·5–8 5 homografts 30 days after insertion. Grouped by 5 mm. intervals.

B HOMOGRAFTS

(i) *Behaviour of Homografts as Compared with Autografts*

Pieces of fresh nerve transplanted to fill a nerve gap in another individual of the same species become like autografts, united with the host nerve. Thereafter their behaviour differed somewhat from that of an autograft. Sanders and Young (1942) and Gutmann and Sanders (1942) made detailed comparisons of such grafts with similar sized autografts by both functional and histological criteria often by means of paired grafts implanted in the same animal.

The chief feature of the reaction of the rabbit to homografts was its extreme variability In favourable cases the distances reached after 15 or 25 days by new nerve fibres growing through such grafts were as great as those given by autografts (Fig 110) Most grafts examined at these times,

however showed shorter distances of outgrowth and, when treated statistically the data as a whole gave evidence of a significant variability not under experimental control. Thus Sanders and Young (1942) were unable to obtain a reliable value for the rate of outgrowth of pain fibres through homografts.

Recovery both of motor function and of cutaneous sensibility nevertheless followed the insertion of 2 cm homografts into the lateral popliteal nerve of the rabbit. After seven such grafts investigated by Gutmann and Sanders (1942) recovery of toe spreading occurred in six The first detectable sign of the reflex appeared between 70 and 125 days after grafting (Fig. 105 p 136), and was followed by a marked improvement in the amplitude of the reaction, although, as in the case of autografts, full normality was never achieved Four of the six animals which showed motor recovery had some return of cutaneous sensibility in two it was complete, in the other two partial.

The variability in the distance reached at a given time by new fibres growing through homografts was reflected in their histological appearances. Wallerian degeneration in homografts appeared to take place more slowly than in autografts unbroken myelin segments could be found in such a graft at 25 days (Fig. 111) and the results of this delayed degeneration could still be seen later Even at 60 days after implantation a graft often contained large spaces full of active macrophages (Fig. 112) and specimens removed as late as 200 days contained similar though smaller macrophage-filled spaces (Fig. 113) It was uncertain, however how far these later appearances were a manifestation of the process of Wallerian degeneration which although slow was fairly normal in its early stages and how far they were a result of a specific reaction of the host to the graft as a result of which the latter was destroyed and partly replaced by host tissue. (See pps 141–149)

By far the most striking histological feature was the invasion of the homograft by lymphocytes The degree of invasion was very variable. In the best cases the infiltration was minimal but in the less favourable cases the whole graft was distended by a mass of lymphocytes and its internal architecture was considerably disturbed (Fig 114) Patches of necrosis also occurred within the graft, proportional in extent to the intensity of the cellular reaction. Although the lymphocytic infiltration subsided fairly quickly it resulted in some degree of fibrosis of the graft, and the innervation was less uniform than in autografts Although new fibres were able to penetrate homografts and to become myelinated within them, there were parts of such grafts containing only small fibres or none at all and there were generally fewer fibres at the centre of the graft. Gutmann and Sanders (1943) found that the largest myelinated fibres in a homograft 200 days after insertion were smaller than in an autograft.

Thus, in the rabbit recovery after fresh homografts is variable yet they are able to conduct new nerve fibres across a gap of 2 cm in sufficient numbers to produce a return of motor function and of sensibility only a little inferior to that of autografts

(ii) Nature of Homograft Reaction

The success of nerve homografts in animal experiments is not equalled by any similar result in man (Sanders 1942 Seddon and Holmes, 1944 review of literature by Seddon 1947 b) Very few human nerve homografts have been followed by any recovery of function that could be unequivocally ascribed to the affected nerve. Sections of such grafts removed at long intervals after



Fig. 111. Distal part of a 2 cm. homograft after 25 days showing delayed and abnormal disintegration of myelin.

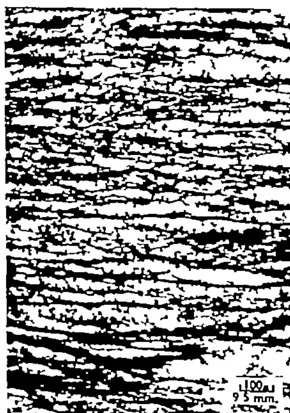


Fig. 112. Part of a homograft after 60 days showing large spaces filled with macrophages which cause considerable deviation and branching of nerve fibres and columns of Schwann cells.

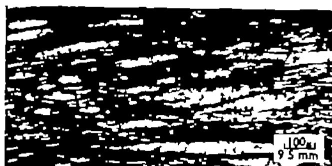


FIG. 113 Part of a homograft after 200 days. Spaces still contain macrophages.



FIG. 114 Part of a 2 cm. homograft after 25 days showing extensive round-cell infiltration and necrosis.

insertion have shown them to be mainly converted into fibrous strands (see Fig 124) However some light is thrown on this discrepancy when we consider the nature of the host reaction to homografts.

In the case of skin transplants Medawar (1944 1945) has shown that homografts behave at first very like autografts, the grafts healing securely and even giving rise to epithelial proliferation. However after a variable period, an acute inflammatory reaction sets in, and the whole native cell population of the graft is destroyed The inflammatory process includes first of all vascular and lymphatic proliferation a massive invasion of the graft by lymphocytes and monocytes of host origin severe oedema, and a general mobilization of mesenchyme cells. At the close of this phase a stagnation and obliteration of the vascular system of the graft, together with the death and necrosis of its constituent cell population takes place Later homografts are invaded anew by fresh vessels from the host, and lymphocytes and monocytes pass through their walls to establish a secondary cell population within the graft.

The whole reaction of the host to the grafted foreign tissue is suggestive of an *actively acquired immune reaction* and, consequently depends quantitatively upon the amount of foreign tissue transplanted Thus a single small homograft of skin may survive for many days without destruction while larger amounts of tissue—whether transplanted as a single large, or as many separate small grafts—undergo a much more rapid breakdown Moreover second set

grafts from a given donor to a host already immunized by grafts from that donor break down even more quickly Such observations are of particular interest since in the case of nerve grafts, one of the main features distinguishing human and animal homograft experiments has been the size of the transplants used Most animal experimenters have used small thin grafts 2 to 3 cm long, while most of the grafts used to repair human nerve defects have been at least 8 to 10 cm. long, and of correspondingly greater diameter Such grafts represent a much greater dosage of foreign tissue than has been used in animal experiments, and if nerve homografts behave similarly to skin grafts the more rapid breakdown of such large grafts might be expected to affect recovery adversely It is interesting to note in this connexion that the only human nerve homografts to show any convincing evidence of recovery were three of Duel s (1934) six cases of facial nerve homografting. In all of these the dosage of tissue was low the nerve transplanted was of small diameter and the gap to be bridged was short.

In further experiments (Sanders, unpublished) comparisons were made in the rabbit between long (5 cm.) and short (2 cm) homografts in the lateral popliteal nerve, the fate of the grafts being followed for as long as 400 days after operation The distance reached after 30 days by new fibres growing through 5 cm homografts was less than that reached 5 days earlier when 2 cm grafts were used (Fig 110) Indeed in three out of fourteen long grafts fibres had not crossed the upper junction at this time.

Eight long grafts showed some sign of return of motor function, but this was delayed in onset (85 to 255 days) as compared with short grafts (70 to 125 days) (Fig. 105) Moreover the quality of recovery finally attained was much inferior to that after short grafts, and in four out of the eight cases did not surpass that achieved following the unaided union of stumps. Three animals showed some improvement, but in only one was the recovery seen equivalent to that shown by short homografts or by autografts. None of the eight animals showed any return of cutaneous sensibility

Histological investigation of the inflammatory changes that take place within nerve homografts has shown that the response of the host tissue to such grafts resembles that seen in skin homografts (Medawar 1944 1945) With nerve, the reaction was complicated by the activity of the nerve fibres and Schwann cells of the host nerve into which the graft was inserted. In the case of a nerve homograft, primary union between the graft and the host nerve took place Wallerian degeneration began within the graft, together with proliferation of its Schwann cells. New blood vessels, coming mainly from the stumps, grew into the graft, and nerve fibres from the proximal stump crossed the upper junction, started to travel down the Schwann tubes of the graft and to *myelinate* within it (Fig. 115) The lower junction was made by Schwann cells from both the graft and the distal stump

Along with these changes, and at a rate and with an intensity dependent upon the size of the graft the inflammatory reaction developed (Fig. 114) *Mononuclear* cells poured out from the blood vessels into the graft which also became oedematous. The reaction was most intense at the junctions which at 25 days were markedly swollen and packed with lymphocytes (Fig. 116) *Large, dilated* blood vessels were found within the graft, especially in the neighbourhood of the junctions (Fig. 117) At the height of the reaction, the walls of the vessels broke down and local haemorrhages occurred within the graft (Fig. 118) At this time the native cell population of the graft was destroyed (Fig. 119) At this



FIG 115 Part of a 2 cm. homograft near the proximal junction after 25 days, showing myelination of new fibres entering graft. Proximal end of the graft to the left.



FIG. 116. Proximal junction of a 2 cm homograft after 25 days showing considerable oedema and round-cell infiltration

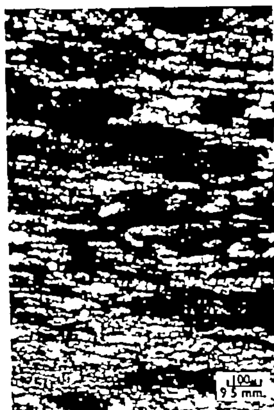


FIG. 117 Part of a 5 cm. homograft after 30 days showing large dilated stagnant blood vessels within the graft close to the proximal junction.

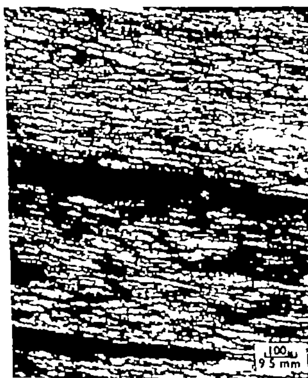


FIG 118 Part of a 5 cm. homograft after 30 days showing stagnant blood vessels and perivascular haemorrhages.

time therefore, new nerve fibres and Schwann-cell strands from the host nerve which latter had invaded the graft from its two ends, became exposed to an environment in which the only structures maintaining the continuity of the nerve were the collagenous tubes of the graft. In the case of short grafts this was not serious, since fibre and Schwann-cell continuity was established throughout the length of the graft by cells of host origin in the period before breakdown took place (Figs. 120 and 121) These structures seemed relatively unaffected by the short period of ischaemia which resulted from the breakdown of the blood vessels of the graft since short nerve homografts removed at long intervals after insertion resemble autografts, having been repopulated by cells from the host nerve. The accumulations of macrophages seen in such grafts in the later stages (Fig. 112) were probably concerned in the removal of the dead and necrotic remnants of the original graft contents (see p 141) The fate of the graft collagen was less certain Medawar (1945) found that the collagen of skin homografts was eventually removed and replaced by host collagen although this took place much later than the destruction of the cells of the graft phagocytosis of the graft collagen fibres did not take place It is possible that the collagenous framework of nerve grafts is also replaced by host collagen If so the new collagen must be laid down in the pattern of the old since the latter undoubtedly acts as a guide for the new nerve fibres and Schwann cells as they traverse the graft.

The inflammatory reaction was more intense, and came on earlier in long grafts, presumably on account of the bigger dosage of homologous tissue Primary vascular breakdown, and destruction of the cells of the graft, took place before the graft had been thoroughly penetrated by either blood vessels Schwann cells or nerve fibres. Thus there were regions in the middle of a long nerve homograft which had been avascular ever since transplantation, and which did not contain any cells (Fig. 122) Such regions subsequently became heavily collagenized (Fig 123) and acted as a barrier to regeneration As a result of this process a long nerve graft examined at a late stage was found to consist of a densely fibrosed strand at either end of which were short segments resembling normal nerve (Fig. 124) The segment at the proximal end resembled a re-innervated distal stump and contained many nerve fibres of various diameters that at the distal end consisting of shrunken Schwann tubes containing strands of Schwann cells originating from the distal stump resembled a degenerated distal stump of long standing (Holmes and Young, 1942) Similar histological appearances were found in human nerve homografts removed following the failure of regeneration (see p 154) which indicated that such processes may also occur in man However the function of a nerve graft is to act as a scaffolding for new fibres and Schwann cells, and to provide an environment in which the nerve fibres can acquire diameters and medullation appropriate to their peripheral connexions—not, as in a skin graft, to provide a supply of living cells. What militates against the success of a large nerve homograft is not necessarily the death of its constituent cell population, but collagenization of part or all of the graft. It is possible that some treatment of homografts which would render them non-antigenic and incapable of provoking an immune reaction but which would not denature the proteins of the graft framework and so initiate a foreign body reaction to the transplant, might improve the prospects of success.



FIG. 119 Part of a 5 cm. homograft after 30 days showing stagnant dilated vessels and necrosis of the cells of the graft.

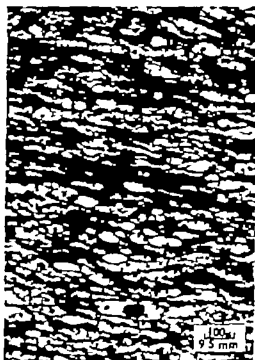


FIG. 120. Proximal portion of a 2 cm. homograft after 30 days. New nerve fibres and strands of Schwann cells derived from the host run in the collagenous tubes of the graft amid macrophages which are removing the contents of the graft.



Fig 123 Central part of a 5 cm. homograft after 200 days the whole graft is converted into a thick fibrous band.



Fig. 124 Appearance of a human nerve graft after 425 days it consists mostly of a thin fibrous strand.

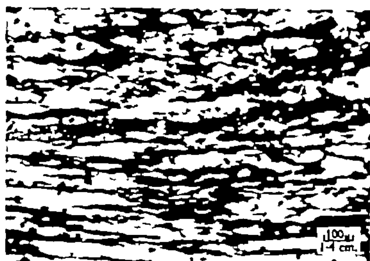


Fig 121 Distal portion of a 2 cm. homograft after 30 days. New columns of Schwann cells traceable into the distal stump below run between macrophages which are removing the remains of the native neural elements of the graft.



Fig 122. Central part of a 5 cm. homograft after 30 days It is completely necrotic.

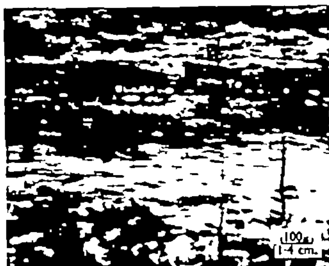


Fig 123 Central part of a 5 cm. homograft after 200 days the whole graft is converted into a thick fibrous band.

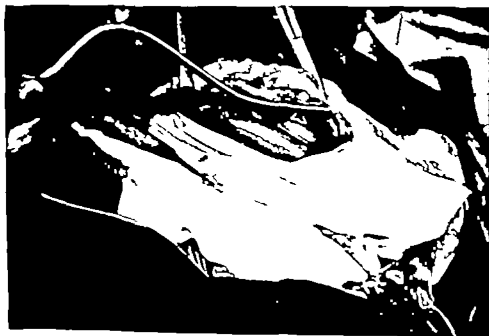


Fig. 124 Appearance of a human nerve graft after 425 days it consists mostly of a thin fibrous strand.

(iii) *Attempts to Mitigate Homograft Reaction*

Very little work has been done in the past with the specific aim of mitigating the host reaction to nerve homografts Most authors who have investigated the behaviour of treated homografts have been concerned with procedures for the storage of grafts (Sanders 1942) However certain of these storage procedures seem to modify the ability of such grafts to elicit a homograft reaction. Sanders and Young (1942) and Gutmann and Sanders (1942) studied the behaviour of grafts of rabbit nerve which had been stored in Ringer's solution at 0°C. for one to three weeks before implantation. Fibres grew readily through such grafts, and occasionally gave rates of growth as high as those obtained with autografts. Motor recovery also followed this type of graft in eight out of eight cases, the time of onset varying between 61 and 117 days compared with 56 to 85 days after suture. The quality of recovery was intermediate between that after fresh homografts and autografts. On the sensory side, out of six cases, one recovered completely two incompletely and three failed

One of the effects of storage in Ringer's solution was a reduction of the lymphocytic reaction (the extent of the reaction became progressively less with an increasing period of storage) with the result that grafts stored for two and three weeks made very clear junctions with the host nerve, accompanied by minimal deviation of fibres (Fig 125) However a feature of the early stages of re-innervation of such grafts was an excessive invasion by macrophages, this being most marked in the grafts stored for longer periods (Fig. 126) At late stages there was no sign of this macrophage reaction and the grafts resembled normal peripheral stumps Many Schwann cells were found in these grafts, and new fibres were able to medullate within them.

Similarly Weiss (1943 a) and Weiss and Taylor (1943) found a reduction in the reaction to homografts which had been dried from the frozen state and subsequently rehydrated Not only did new nerve fibres and Schwann cells grow through such grafts but in both cats and monkeys functional recovery was found following their use. However in all of the above experiments the grafts used were short (less than 3 cm.) and experiments with longer grafts have failed to show any superiority of frozen-dried over fresh homografts. Sanders (unpublished work) compared the functional results of 5 cm. long frozen-dried homografts of rabbit medial popliteal nerve with those of 5 cm. grafts of fresh nerve taken from the same donor and grafted into a litter mate of the recipient of the frozen-dried graft. The mean time of onset of recovery after fresh grafts was 143 days Although the frozen-dried grafts gave a slightly earlier time of onset of recovery 101 $\pm$ 10 days (Fig. 105 p 136) differences of this magnitude would be expected to occur by chance alone in 5 to 10 per cent of cases. Similarly there was no significant difference in the quality of functional recovery achieved

Histologically there was little to choose between fresh and frozen-dried homografts when examined in the late stages of regeneration The latter although penetrated by a fair number of nerve fibres and Schwann cells were as heavily fibrosed as fresh grafts In the early stages however there was much less lymphocytic reaction than was seen with fresh grafts.

In a further series of experiments a comparison was made between fresh homografts and similar grafts which had been subjected to five successive cycles of freezing and thawing immediately before implantation The distances reached after 30 days by fibres growing through 6 5 to 8 5 cm. grafts were measured and the distances reached in the two cases are shown in Fig. 127 That reached by fibres growing through fresh grafts was highly variable, the mean distance



FIG. 125 Proximal junction of a homograft stored in Ringer's solution for 7 days at 2° C before insertion. Little reaction 25 days later

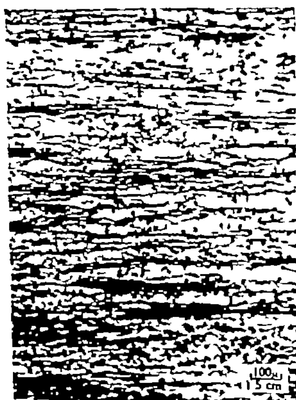


FIG. 126 Part of a homograft stored for 21 days before insertion. Note Schwann nuclei, absence of lymphocytes, presence of many macrophages and some nerve fibres.

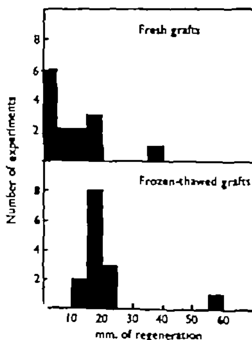


FIG. 127 Histograms to show the frequency with which nerve fibre outgrowths of each distance were obtained through (*a*) fresh homografts, and (*b*) frozen-thawed homografts 30 days after insertion. Grouped by 5 mm intervals.

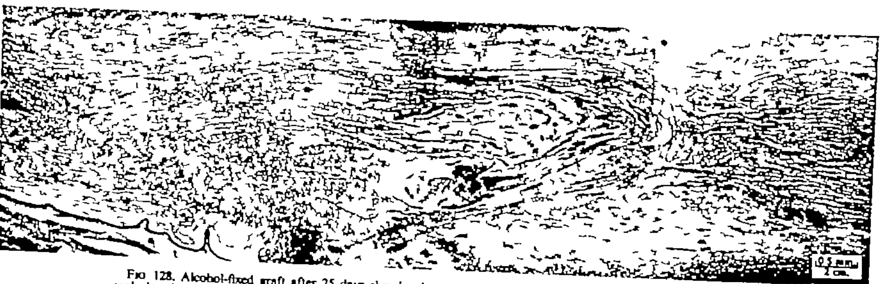


FIG 128. Alcohol-fixed graft after 25 days showing how new fibres grow out through a bed of macrophages replacing the graft. The proximal stump has put out bundles of new fibres the other and lateral portions of the graft have already been removed. Graft on the left, proximal stump of the nerve on the right.

being 9·5 mm Fibres had grown somewhat further through the frozen thawed grafts (mean distance of outgrowth 20·0 mm) and the difference between the two types of graft was statistically significant ($t = 6{\cdot}692$ $P = 0{\cdot}001$) Histologically the frozen thawed grafts did not elicit a homograft reaction although they were penetrated by Schwann cells and new fibres. There was, however an excessive number of macrophages in these grafts concerned presumably with the removal of the dead graft contents.

No functional results for this latter procedure are at present available, and further work will be necessary before the value of frozen thawed grafts can be estimated.

C HETEROGRAFTS

Heterografts do not make proper unions with the host nerve, and do not degenerate. They set up a violent reaction and are eventually removed New nerve fibres grow around but not through them (Sanders and Young, 1942) They have been followed by such uniformly bad results in both animals and man that their use need no longer be considered

D GRAFTS OF ALCOHOL AND FORMALIN FIXED TISSUE

Grafts of these types, like heterografts should no longer be used Alcohol fixed grafts do not become innervated but are progressively removed by macrophages attacking from the ends and also from the sides Subsequently the bed of macrophages is invaded by Schwann cells from both stumps and nerve fibres growing out from the central stump These proliferations meet as the graft is progressively removed and it is through them, and not through the graft that innervation of the peripheral stump occurs (Fig. 128) Gutmann and Sanders (1942) made four of these grafts in two a delayed motor recovery of a poor quality occurred which was equivalent to that achieved by the unaided union of stumps there was no sensory recovery

The type of graft introduced by Gosset and Bertrand (1937 1938)—i e rabbit or cat spinal cord fixed in formol and stored in 50 per cent alcohol—gives the most unfavourable reaction of any type of nerve graft, and in the rabbit the prospects for recovery are even worse than for alcohol fixed grafts There is accordingly no biological foundation for the procedures suggested by Propper Grashchenkov (1942) and this type of graft cannot be considered to have clinical possibilities

2. Histological Condition of Nerve Grafts in Man

Autografts even when they consist of nerve segments of considerable thickness, offer considerable prospects of success in the repair of human nerve lesions. Seddon Young, and Holmes (1942) examined a cable autograft removed seven months after being used to bridge a gap in a human median nerve and found that the transplanted tissue had survived, Schwann-cell proliferation and the removal of myelin having proceeded normally New nerve fibres had entered the graft and had become myelinated therein. Holmes (1947a) described the histological condition of five further autografts Two of these consisted of two parallel lengths of the lateral popliteal nerve, used to repair gaps in the medial popliteal nerve after injuries inflicted 16 and 22 months previously which had divided both divisions of the sciatic nerve. One of the grafts was taken from the proximal stump of the lateral popliteal and so was normal when transplanted the other three grafts were taken from the distal stump and were predegenerated All

were examined by the technique of nerve biopsy (Holmes and Zachary 1946 Holmes 1947 b) The grafts made with predegenerated nerve were abundantly innervated by large fibres The graft made with fresh nerve was less satisfactory and contained the remains of nerve fibres which had failed to undergo normal Wallerian degeneration. At no point in the nerve was there any evidence of regeneration, and the distal stump below the graft contained very few new fibres.

An experimental transplant, consisting of a segment of the posterior inter osseous nerve sutured to a normal proximal stump was found after five weeks to be abundantly re-innervated and normal in all respects. A similar experimental autograft made with 7 cm. of nerve which had been predegenerated for 613 days, was examined seven months after grafting by Barnes, Bacsich, and Wyburn (1945) and found to be well innervated In this case the new fibres within the graft had failed to myelinate, probably on account of the long period of degeneration undergone by the stump used as a graft (Holmes and Young, 1942) Two other grafts studied by Holmes (1947 a) were segments of the radial nerve transplanted into subcutaneous tissue and not connected to any stump After seven and twelve weeks they showed some abnormalities of degeneration, but none so severe as to prevent their acting as successful nerve grafts.

The evidence presented above shows that autografts may offer considerable prospects of success for the repair of human nerve defects. All the histological abnormalities found are the result of interference with the normal course of *Wallerian degeneration and may be the result of defective vascularization* It seems possible that predegenerated grafts may be able to survive the initial period of avascularity better than grafts of fresh nerve, particularly where large transplants are used. Long standing degeneration may be harmful (Holmes and Young, 1942) but the condition of a long degenerated graft cannot be worse than that of the host distal stump through which fibres must also grow if a useful functional result is to be achieved.

In marked contrast to the results of autografts, all of the fourteen human homografts which have been examined histologically have been unmitigated failures (Seddon and Holmes, 1944 Barnes, Bacsich and Wyburn, 1945 Spurling, Lyons Whitcomb and Woodhall 1945) Although the human homografts were examined after too long an interval to show the primary cellular reaction characteristic of rabbit nerve homografts (see p 140) there is evidence that similar processes may be characteristic of human nerve homografts and be responsible for their failure For example, neurotization of the proximal segment of the graft occurred to a varying extent, but in all cases necrosis and fibrosis of part of the graft took place with the resulting development of a fibrous barrier to regeneration within the graft which prevented new fibres from reaching the distal stump The severity of these reactions was in general proportional to the size of the transplant used This was shown most clearly by the distances reached by new fibres growing through these grafts. In Fig. 129 the distances reached by new fibres is plotted against the length of the graft used, and it will be seen that, generally speaking, there is an inverse relationship between the size of the graft and the distance reached by new fibres growing within it. The relationship may in fact be more marked than that shown in Fig. 129 The cases of Spurling *et al* (1945) which together form the group of short grafts in which some outgrowth had occurred, were mostly excised after shorter periods of regeneration than those of the other authors. Had they been allowed to remain longer in the host, they might have shown still greater

distances of outgrowth Barnes *et al* (1945) describe an 18 cm graft but this is exceptional in that it was penetrated by new fibres to a distance of 25 mm while neither of the large grafts of Seddon and Holmes (1944) showed any regeneration whatsoever However the whole reaction to this graft was milder than in the other large grafts studied and may indicate a closer compatibility between the tissues of donor and host than in the other cases All of these appearances are consistent with the view advanced above that the constituent cells of a homograft are destroyed as a result of an immunity reaction on the part of the host, the severity and rapidity of onset of the reaction depending both upon the amount of tissue transplanted and on the genetic relationship between donor and host Until there has been further investigation of the processes governing this reaction and treatments have been devised for its modification, the use of homografts in man is contra indicated

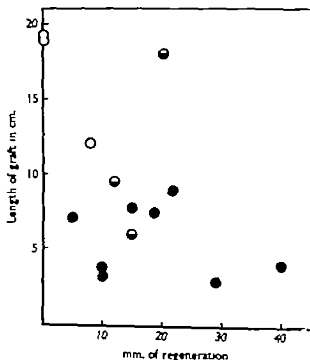


FIG. 129 Diagram to show the correlation between the length of a human nerve homograft and the distance reached by nerve fibres growing within it. Open circles—cases of Seddon and Holmes (1944) half-filled circles—cases of Barnes, Bacsich, Wyburn and Kerr (1946) filled circles—cases of Spurling, Lyons, Whitcomb and Woodhall (1945)

were examined by the technique of nerve biopsy (Holmes and Zachary 1946 Holmes 1947 b) The grafts made with predegenerated nerve were abundantly innervated by large fibres. The graft made with fresh nerve was less satisfactory and contained the remains of nerve fibres which had failed to undergo normal Wallerian degeneration. At no point in the nerve was there any evidence of regeneration and the distal stump below the graft contained very few new fibres.

An experimental transplant, consisting of a segment of the posterior inter osseous nerve sutured to a normal proximal stump was found after five weeks to be abundantly re innervated and normal in all respects. A similar experimental autograft, made with 7 cm of nerve which had been predegenerated for 613 days was examined seven months after grafting by Barnes, Bacsich and Wyburn (1945) and found to be well innervated In this case the new fibres within the graft had failed to myelinate, probably on account of the long period of degeneration undergone by the stump used as a graft (Holmes and Young, 1942) Two other grafts studied by Holmes (1947 a) were segments of the radial nerve transplanted into subcutaneous tissue and not connected to any stump After seven and twelve weeks they showed some abnormalities of degeneration but none so severe as to prevent their acting as successful nerve grafts.

The evidence presented above shows that autografts may offer considerable prospects of success for the repair of human nerve defects. All the histological abnormalities found are the result of interference with the normal course of Wallerian degeneration, and may be the result of defective vascularization. It seems possible that predegenerated grafts may be able to survive the initial period of avascularity better than grafts of fresh nerve, particularly where large transplants are used Long standing degeneration may be harmful (Holmes and Young, 1942) but the condition of a long degenerated graft cannot be worse than that of the host distal stump, through which fibres must also grow if a useful functional result is to be achieved

In marked contrast to the results of autografts, all of the fourteen human homografts which have been examined histologically have been unmitigated failures (Seddon and Holmes 1944 Barnes, Bacsich, and Wyburn, 1945 Spurling, Lyons, Whitcomb and Woodhall 1945) Although the human homografts were examined after too long an interval to show the primary cellular reaction characteristic of rabbit nerve homografts (see p 140) there is evidence that similar processes may be characteristic of human nerve homografts and be responsible for their failure. For example, neurotization of the proximal segment of the graft occurred to a varying extent, but in all cases necrosis and fibrosis of part of the graft took place, with the resulting development of a fibrous barrier to regeneration within the graft which prevented new fibres from reaching the distal stump The severity of these reactions was in general proportional to the size of the transplant used. This was shown most clearly by the distances reached by new fibres growing through these grafts. In Fig. 129 the distances reached by new fibres is plotted against the length of the graft used, and it will be seen that, generally speaking, there is an inverse relationship between the size of the graft and the distance reached by new fibres growing within it. The relationship may in fact be more marked than that shown in Fig. 129 The cases of Spurling *et al* (1945) which together form the group of short grafts in which some outgrowth had occurred, were mostly excised after shorter periods of regeneration than those of the other authors. Had they been allowed to remain longer in the host, they might have shown still greater

distances of outgrowth Barnes *et al* (1945) describe an 18 cm graft but this is exceptional in that it was penetrated by new fibres to a distance of 25 mm while neither of the large grafts of Seddon and Holmes (1944) showed any regeneration whatsoever However the whole reaction to this graft was milder than in the other large grafts studied and may indicate a closer compatibility between the tissues of donor and host than in the other cases All of these appearances are consistent with the view advanced above that the constituent cells of a homograft are destroyed as a result of an immunity reaction on the part of the host the severity and rapidity of onset of the reaction depending both upon the amount of tissue transplanted and on the genetic relationship between donor and host. Until there has been further investigation of the processes governing this reaction, and treatments have been devised for its modification the use of homografts in man is contra indicated

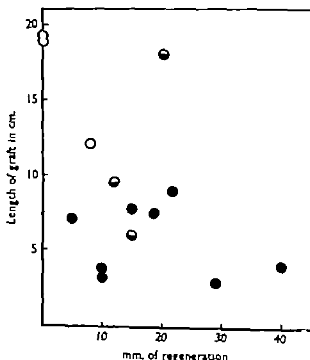


FIG 129 Diagram to show the correlation between the length of a human nerve homograft and the distance reached by nerve fibres growing within it. Open circles—cases of Seddon and Holmes (1944) half-filled circles—cases of Barnes, Bacsich, Wyburn and Kerr (1946) filled circles—cases of Spurling, Lyons, Whitcomb and Woodhall (1945)

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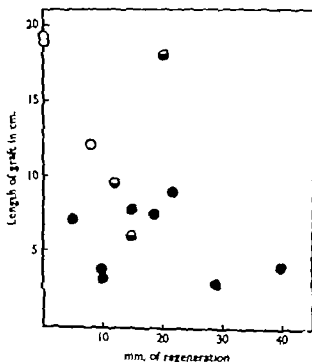


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IV

CAUSALGIA A REVIEW OF 48 CASES

by R. Barnes

1 Introduction

AFTER an injury to a peripheral nerve a patient may complain of intense and persistent pain in the hand or foot of the injured limb The condition was first described by Paget in 1864 and in the same year Mitchell *et al* gave a classical description of the malady which they named Causalgia

In this survey the term causalgia has been reserved for pain following an injury of a nerve trunk, which has the following characteristics

(1) It is severe, spontaneous and persistent.
(2) *It usually has a burning quality*
(3) It may spread beyond the territory of the injured nerve or nerves.
(4) It is invariably aggravated by both physical and emotional stimuli.

This definition differs in one important detail from the description of Weir Mitchell. He regarded burning pain as an essential feature of causalgia. Although most of these patients did complain of burning pain it was not considered one of the essential criteria of diagnosis. There were some patients who described the pain as throbbing, bursting, clamping, stabbing, tearing, or gnawing in quality Aggravation of the pain by emotional stimuli was regarded as far more important in the diagnosis of causalgia, for this feature excluded a number of other painful post traumatic lesions of the peripheral nerves, *which are not* relieved by sympathectomy

This summary is based on a study of 48 cases selected from a larger group because the case records were more complete. Although it has not been possible to estimate the true incidence of causalgia observers at all five centres are agreed that it is not a frequent complication of the peripheral nerve injuries of warfare.

2. Clinical Features

(i) *Quality of Pain*

One of the major difficulties *in a study of causalgia is that the diagnosis* and the assessment of results of treatment must, of necessity be based largely on subjective evidence. Patients vary greatly in their ability to describe with accuracy the quality of pain and for this reason it has not been insisted upon that the pain of causalgia must have a burning quality

(ii) *Factors Modifying Pain*

In severe causalgia there is a general lowering of the threshold for all sensory stimuli. The lightest touch or vibration, such as is caused by sneezing or coughing, may aggravate the pain and extremes of temperature, particularly heat, are badly tolerated. All movements of the affected limb are sedulously avoided. The arm is held close to the side with the elbow flexed at a right angle and the hand supported to guard against unexpected jarring movements if the leg is affected the patient lies with the knee and ankle flexed, and the outer border of the foot resting on the bed.

Many of the worst afflicted seek relief from the pain by cold wet applications to the hand or foot Warm water is often equally effective and may be preferred for relief of pain appears to be due to the sensitivity of the part being reduced by the moisture rather than by the coolness of the application

Causalgic pain is aggravated by emotional or psychic stimuli and in this respect it differs from all other painful states arising from a nerve injury Noise high notes, low flying aeroplanes or a child s cry may provoke a severe spasm of pain Excitement and worry are badly tolerated and many patients complain that they cannot enjoy the cinema or read an exciting novel Some acquire the habits of a recluse and spend the greater part of the day sitting or lying in a corner of the ward other exhibit a morbid interest in their condition One patient a painter by trade, complained that he had to skip pages of books where there was mention of cliffs heights or ladders, and that the sight of anyone on a ladder caused a spasm of pain Yet he carried a picture of a man standing on a rocky peak when asked about this he would answer I cannot bear to look at that one" Physicians unfamiliar with the syndrome may be inclined to regard this unusual behaviour as a psychoneurotic manifestation

There is, however no evidence to support the view expressed by some authors that the victims of causalgia are of unstable temperament The severity of the pain and the marked lowering of the threshold to all forms of sensory and psychic stimulation are sufficient to sap the morale of the bravest. Moreover it is unusual to find any abnormality in the behaviour of a patient once the pain has been abolished by sympathectomy

(iii) *Distribution of Pain*

The pain was invariably felt in the hand or foot and rarely radiated to the forearm or leg in no patient did it spread to other parts of the body as described by Mitchell *et al* (1864) The pain was usually most severe in the palm of the hand and the sole of the foot, and was often confined to the sensory distribution of the injured nerve or nerves When the patient had an incomplete lesion of both median and ulnar nerves the whole of the palm of the hand was painful whereas only one of the six patients in whom the median nerve was injured alone or in combination with a completely divided ulnar nerve complained of pain in the whole of the palm

(iv) *Time of Onset of Pain*

A number of patients stated that the pain began at the moment of wounding and they were surprised to find that their hand or foot was uninjured In most cases the pain began during the first day and the longest interval between wounding and its onset was seven weeks. The time of onset in the 41 cases in which a record was made was as follows

First 24 hours	26
Second day	4
Third day	4
Fourth to seventh day	1
Eighth to fourteenth day	4
Fifteenth to twenty first day	0
Twenty second to twenty-eighth day	1
At about the seventh week	1

No satisfactory explanation has been found for the considerable variation in the time of onset of the pain. Since the pain usually began within 24 hours

of injury wound infection and intraneural scarring can hardly be blamed. Some patients stated that the whole limb felt numb for some time after wounding, and that the pain was first felt as the numbness wore off several hours or days later It is tempting to link the onset of pain with the restoration of conductivity of the nerve. Unfortunately there was no evidence on this point, since usually several months had elapsed before the patients reached a Nerve Injuries Centre.

(v) *Duration of Pain*

The pain usually increased in severity for the first few hours or days after onset, and persisted for many months. It seldom kept the patients awake at night. Some patients stated that they had "to get awake to the pain and one said that he was only able to live by sleeping most of the time Sleep greatly reduces the activity of the autonomic centres in the hypothalamus and all forms of physical and psychic stimulation

After a period which varied from a few months to a year or more there was often a *slow but steady improvement in the pain. The paroxysms* became less frequent and were better tolerated though for several years after wounding many patients still complained of twinges of pain when they were excited or during hot weather in two patients these were severe enough to justify sympathectomy six years later

(vi) *Trophic Changes*

Since the first description of the condition by (Paget, 1864 Mitchell *ibid.*) the trophic and vascular changes in causalgia have given rise to much comment. Mitchell stated that the pain was usually associated with a glossy skin, and that the temperature of the burning area was always higher than that of the neighbouring skin or of the corresponding part on the normal side. Stopford (1918) was so impressed by the vasodilation in the painful areas that he suggested thermalgia as an alternative name. In the Report of the Medical Research Council (1920) the changes were described as follows

The hand is pink and moist with sweat, skin is thin tight, smooth and glossy *nails are curved, grow rapidly and are exquisitely tender The joints are stiff and swollen, the finger pads wasted so that nail beds protrude, and the bones are* rarefied and brittle "

Recent investigators have pointed out that these trophic changes are by no means a constant feature of causalgia and this has been confirmed by this study In some cases the 'trophic changes were severe, but they appeared to be related to the severity of the neural injury or to the patient s unwillingness to use the painful limb The smooth shiny skin, stiff joints, and wasted muscles and finger pulps were *identical with those of any painful condition* which imposed a similar degree of immobility on the joints or soft tissues.

The intense osteoporosis which was a feature of some cases may be attributable to disuse. It cannot be produced by nervous action as suggested by Sudeck (1938) or Turner (1936) for the osteoporosis was not confined to the painful areas and sometimes affected the whole limb nor was there any difference in the degree of bone atrophy in the little finger as compared with the rest of the hand in the cases of *median nerve causalgia in which* the ulnar nerve was severed.

The changes in skin temperature and sweating were of great interest. In only a few patients was there the increased sweating and warmth of the affected part

described by the earlier writers Sometimes the hand or foot was cooler than its fellow in others it was unchanged or varied from day to day Perspiration also varied from extreme hyperidrosis, with drops of sweat forming on the tips of the fingers, to a completely dry skin There was no correlation between the skin temperature and the degree of sweating. These observations were in agreement with those of Shumacker Speigel and Upjohn (1948) and other writers

Rasmussen and Freedmann (1946) and White Heroy and Goodman (1948) have suggested that the changes in skin temperature and sweating may be related to the time that has elapsed since injury In most of Rasmussen and Freedmann s early cases the painful part was warm and pink, but after several months became cold and blue Most of White s cases were seen many months after injury and all had cold moist extremities. It was not possible to confirm these observations. There was no significant difference in the duration of symptoms in the cases in which the affected part was warm as compared with those in which it was cold

Richards (1946b) has pointed out that the vasomotor manifestations of an incomplete peripheral nerve lesion are numerous. Lewis (1937) has shown that stimulation of the distal end of a divided sensory nerve causes vasodilation in the area of skin to which the nerve is distributed which may be accompanied by burning pain it was thought to be due to the release of a histamine like substance in the skin which lowers the threshold of the pain nerve endings It is now known that impulses may pass from one nerve fibre to another at the site of a nerve lesion and it is possible that this may be the source of the antidromic impulses. Furthermore, White and Smithwick (1944) have shown that any form of severe pain will cause reflex sweating and vasoconstriction In these circumstances it is not surprising that the vasomotor and sudomotor manifestations of causalgia are so variable.

(vii) *Sensibility*

Many of the patients were so apprehensive of any form of stimulus that it was impossible to perform an adequate sensory examination while the pain persisted In some patients there appeared to be extreme hyperaesthesia and hyperalgesia of the hand or foot, any approach to it causing withdrawal with expressions of pain Yet once their confidence was gained it was found that when the eyes were closed there were varying degrees of loss of appreciation of pin-prick and light touch in the painful area, though when the eyes were open these caused great pain In these patients the hyperaesthesia and hyperalgesia were abolished by an effective sympathectomy confirming that the painful sensations were not primarily due to the lesion of the somatic nerve fibres. In most patients there was some impairment of sensibility which varied from loss of light touch to complete insensibility in a part or the whole of the sensory distribution of the injured nerves In some patients impaired sensibility and an abnormally painful response to sensory stimuli persisted after an effective sympathectomy These paradoxical findings may be explained by the somatic nerve fibres having sustained varying degrees of injury which may have caused some of them to loose their conductivity while others were in an irritative phase

(viii) *Motor Paralysis*

The testing of muscle power was also beset with difficulties. Movements of the painful part often caused a severe spasm of pain, which sometimes resulted in a reflex inhibition of many of the muscles of the limb and was not confined to those supplied by the affected nerve. This no doubt accounted for the extensive

wasting of the muscles which was a striking feature in some patients The extent of the motor paralysis was very variable in some there was little or no loss of power in others, and especially in cases of causalgia of the lower limb the paralysis was more extensive. Even when the paralysis appeared initially to be fairly complete some recovery always occurred in the proximal muscles supplied by the injured nerve.

3 Description of Nerve Lesion

In all the cases in this series there was a lesion of either the brachial plexus or the median sciatic, medial popliteal or posterior tibial nerves. None of the nerves was completely divided and all of them eventually showed partial or complete spontaneous recovery of function All the wounds were caused by bomb or shell fragments or high velocity missiles

TABLE 27a

Type and level of nerve lesion in cases of causalgia in upper limb

Type of lesion	No of cases	Level of lesion						
		Axilla or higher	Upper third arm	Middle third arm	Lower third arm	Elbow	Upper arm (unstated)	Fore arm
Median, Ulnar	9	3	—	2	1	—	2	1
Median, Ulnar*	3	1	—	—	2	—	—	—
Median, Ulnar, Radial	7	3	3	1	—	—	—	—
Median, Ulnar, Radial	1	1	—	—	—	—	—	—
Median	3	1	1	—	—	—	1	—
Median, Ulnar, Radial, Musculo-cutaneous*	1	—	1	—	—	—	—	—
Median, Internal cutaneous	1	—	—	—	—	1	—	—
Brachial plexus	2	2	—	—	—	—	—	—
Total	27	11	5	3	3	1	3	1

* Divided nerve

(*a*) *Upper limb* (*Table 27a*)

In brachial plexus injuries the lesion involved the lowest trunk or inner cord These nerves carry most of the autonomic fibres to the arm or hand and they pass to their ultimate destination via the median and ulnar nerves, of which the median contains by far the greater number

In all but four of the 25 lesions of the median nerve there was an associated injury of the ulnar The ulnar nerve was divided in three the remainder were lesions in continuity of varying degrees of severity

The median nerve was exposed in 17 patients *In four* it appeared normal in the others there were varying degrees of intra and extraneural scarring, and in some a neuroma which did not involve the whole thickness of the nerve

All the injuries occurred at or above the level of the elbow joint with the exception of one case, a lesion of the median and ulnar nerves, in the middle third of the forearm (Table 27a)

(*b*) *Lower limb* (*Table 27b*)

In every sciatic nerve injury there was clinical evidence of a lesion of both the medial and lateral popliteal divisions. In five patients there was a transient paralysis of all the muscles supplied by the sciatic nerve. In the remainder the lesion was more severe and the paralysis was more pronounced in the muscles supplied by the medial popliteal division. The sciatic nerve was exposed in eight patients One nerve appeared normal in the others there were varying degrees of intra and extraneural scarring and in two cases there was a neuroma which did not involve the whole thickness of the nerve.

Five patients had an injury of both medial and lateral popliteal nerves and in all of them there was intra and extraneural scarring of the medial popliteal nerve. In two of these patients there was a complete lesion of the lateral popliteal nerve, and a hard neuroma was found, which was treated by resection and suture

The medial popliteal nerve alone was involved in two cases both nerves were explored one was thickened and contained a small foreign body the other was constricted by extraneural scar With one exception all the nerve injuries in the lower limb were at or above the level of the knee joint (Table 27b)

TABLE 27b

Type and level of nerve lesion in cases of causalgia in lower limb

Type of lesion	No of cases	Level of lesion						
		Buttock	Upper third thigh	Middle third thigh	Lower third thigh	Thigh (unstated)	Popliteal fossa	Middle third leg
Medial and lateral popliteal	18	3	1	6	3	1	4	
Medial popliteal	2						2	
Posterior tibial	1							1
Total	21	3	1	6	3	1	6	1

None of the nerves were completely divided

There was a striking similarity in the pattern of the nerve injury in the arm and leg. The main features were as follows

(1) In every case there was an incomplete lesion of the *median or medial* popliteal nerves or their roots or branches. In some cases there was a transient motor paralysis and by the time the patient arrived at the Nerve Injuries Centre the only evidence of neural injury was pain and hyperalgesia in the sensory distribution of the nerve. *Even in the few cases where, at the time of operation, all* muscles were paralysed distal to the injury there was always a lesion in continuity of the nerve with varying degrees of intraneural scarring. In every case there was some subsequent motor recovery These findings are in conformity with *those of Shumacker et al (1948) and of many other authors.*

Causalgia must be a very rare complication after complete division of a peripheral nerve and reports of its occurrence require critical examination, as in the following case

A patient was referred for examination with a diagnosis of ulnar nerve causalgia. Clinically there was complete ulnar palsy and at operation the nerve was seen to be severed. The only evidence of a median nerve lesion was pain and hyperalgesia in the median area of the hand. The pain was abolished for four hours by blocking the median nerve at the wrist with 2 per cent procaine.

(2) *Multiple nerve lesions* were common and the pain was often associated with more than one of them In the upper limb this was demonstrated by blocking in turn the ulnar nerve at the elbow and the median nerve at the wrist. Three patients with incomplete lesions of the median and ulnar nerves were investigated in this manner In two blocking the ulnar and median nerves in succession caused relief of pain in their respective zones of distribution in the third patient the nerve blocks did not relieve the pain though its character was modified.

(3) All the nerve injuries were caused by bomb or shell splinters or other *high* velocity missiles, and with two exceptions all the lesions were at or above the level of the knee or elbow

Ulmer and Mayfield (1946) Sunderland and Kelly (1948) and many others have drawn attention to the rarity of causalgia following a nerve lesion in the distal part of a limb It is unlikely that the greater incidence of causalgia in proximal lesions is connected with any particular relationship between the numbers and arrangement of autonomic and sensory fibres, for most of the autonomic and almost all of the sensory fibres leave the nerve trunks *distal to* the wrist and ankle and it is these fibres that appear to be chiefly concerned in the aetiology of causalgia.

Causalgia is commoner when there is a dual nerve injury and this probably explains the preponderance of high lesions. In the lower limb the medial and lateral popliteal nerves are usually joined to form the sciatic nerve down to the level of the lower third of the thigh and they are closely related in the popliteal fossa. Below this point they diverge and therefore there is less risk of a dual injury The same considerations apply in the upper limb. Here the median and ulnar nerves are closely related in the upper two thirds of the arm below this level they diverge, again reducing the chances of an injury to both nerves.

It is generally agreed that causalgia is a rare complication of an incised wound of a nerve and is more commonly associated with a stretch injury Puckett, Grundfest, McElroy and McMillen (1946) have demonstrated that when a high velocity missile passes close to a nerve the latter is subjected to a considerable degree of stretch, which cannot occur when a nerve is *cleanly divided. A stretch*

injury of this type may cause various degrees of damage to the axons and degeneration of their myelin sheaths. Granit, Leksell and Skoglund (1944) have demonstrated that in these circumstances an artificial synapse may be formed which allows impulses to pass between the various nerve fibres at the level of injury This has an important bearing on the pathogenesis of causalgia and is discussed later

4 Damage to Non-neural Tissues

(1) *Main artery*
Injury of a main artery has been invoked as a cause of burning pain by Leriche (1939) and in some of his cases it was relieved by excision of the damaged segment. Arterial injury could be regarded as an important aetiological factor in causalgia only if it were present in most of the cases. In this series the artery was damaged in only 11 of the 48 cases and always in the upper limb where the brachial artery and median nerve were closely related The arterial injury was probably not significant since there was no evidence of an ischaemic lesion of the nerves or muscles.

(2) *Wound Infection*
Mitchell believed that there was some relationship between causalgia and wound infection The rarity of causalgia in civilian practice lends support to this belief but there are serious objections The pain usually begins within a few hours of wounding and many of the bullet wounds heal in two to three weeks without gross infection. It seems probable that the higher incidence of causalgia in warfare is related to the type of nerve lesion caused by the passage of a missile through the soft tissues in the proximity of a nerve trunk

5 Treatment

Of all the maladies that can afflict man causalgia is one of the most painful and effective treatment should be instituted at the earliest opportunity not only to allay intolerable suffering but also to prevent the crippling deformities of the joints which follow long continued immobilization of the painful limb (Tables 28 and 29)

A review of the literature of causalgia that has appeared during and since the last war and the experience of surgeons working in the Nerve Injuries Centres in Great Britain, leave no doubt that sympathectomy is the only form of therapy likely to be effective in a severe case of causalgia Many other methods of treatment were employed in the Centres They included freeing of the nerve from scar tissue (neurolysis) resection and suture of the damaged segment, periarterial sympathectomy and radiotherapy yet although each of these appeared to relieve pain in isolated cases the effect was never dramatic and might well have been unrelated to the treatment given When assessing the efficacy of any form of therapy in causalgia it is well to remember that the pain seldom continues with its original intensity for more than a few months after injury and that gradual relief of pain is to be expected over many years.

(1) *Neurolysis*
This procedure was based on the belief that the burning pain was caused by extraneural scar constricting the axons or interfering with their blood supply This notion does not explain why the pain often begins within a few hours of injury or those cases in which there is no extraneural scar

T

Clinical features and results of tre

CASE NO.	TYPE OF LESION	DATE OF INJURY	CLINICAL FEATURES: Time of onset of pain	Site of pain	Hand or foot temperature	Sweating	Date of examination	INVESTIGATI… Type
1	Median, Ulnar, Radial	2.11.42	1st day	Palm of hand	Warm	++	29. 7.43	Paravertebral blo… Median nerve blo… Ulnar nerve bloc…
2	Median, Ulnar, Radial*	19. 7.43	7th week	Palm, fingers	Cold	+	25.11.43	Paravertebral blo…
3	Median, Ulnar	11. 4.43	1st day	Forearm, hand	No change	0 median area + ulnar area	16. 8.43	Paravertebral bloc… *All* nerves bloc… with
4	Median, Ulnar*	24. 4.43	3rd day	Hand, especially 4th and 5th fingers	—	++	21.10.43	Paravertebral bloc… Ulnar nerve block Median nerve bloc…
5	Median, Ulnar	17. 4.44	—	Fingers	Cold	—	—	—
6	Median, Ulnar, Radial	16. 7.44	1st day	Forearm, hand Worse in median area	Warm	—	3. 8.44 19. 8.44	Paravertebral block Paravertebral block
7	Median, Ulnar*	29. 7.44	1st day	Centre of palm	—	—	1.10.44	—

KEY— * Divided nerve. Degree of sweating: 0 Anhidrosis ± Variable + Normal or slightly increased ++ Hyperhidrosis

...es of causalgia in the upper limb

...VESTIGATIONS	TREATMENT			FOLLOW-UP	
Result	Date	Type	Result	Date	Result
...mpletely relieved	Nov.–Dec. 1943	Radiotherapy	No effect on pain		
...lieved in median	18. 1.44	Post-ganglionic sympathectomy	Complete relief of pain and hyperalgesia	30. 7.45	Has no pain
...lieved in ulnar					
...rary relief of pain	2. 3.44	Post-ganglionic sympathectomy	Considerable relief of pain—but still complains of aching pain over heads of metacarpals	23. 2.46	Some pain, especi... cold weather
	6. 6.44	Suture of radial nerve	No effect on pain		
...lieved for 1½ hr	Sept.–Oct. 1943	Radiotherapy to hand and nerve lesion	No effect on pain	7. 5.45	Slight pain with ... exercise
...till severe but of ...ent quality	9.11.43	Pre-ganglionic sympathectomy	Partial relief of pain for 2 days Sympathectomy incomplete		Hyperalgesia in p... hand
	13. 1.44	Stellate ganglionectomy	Pain relieved		
...relieved for several ...s	Dec. 1943	Radiotherapy to hand and median nerve lesion	No relief of pain	18. 4.46	Pain in forefinger ...ed 3 months after ...thectomy—but ... severe as formerl... present when ha... and aggravated ... extremes of temp...
...ffect on pain	1. 2.44	Anterior transposition and suture ulnar nerve	Pain relieved for 4 days then as bad as before operation		
...relieved for several ...rs	3. 3.44	Post-ganglionic sympathectomy	Free of pain and hyperalgesia		
—	19. 3.45	Sympathectomy	Complete relief of pain. Slight hyperalgesia remained	11. 1.48	No return of pai... has slight hyper... in fingers
...elief of pain, block ...mplete ...relieved for 24 hr	24. 8.44	Post-ganglionic sympathectomy	Pain relieved but still has intense hyperaesthesia and hyperalgesia in median area. Maximum improvement 3½ months later		Pain returned 8 ... after sympathe... and neurolysis w... formed
	20. 5.47	Exploration brachial plexus, adhesions freed around nerve	Slight relief of pain	5. 5.48	Patient still has a c... erable amount o... but not as severe ... fore sympathecto...
	4. 6.47	Neurolysis median nerve in forearm			
—	20. 9.44	Neurolysis median nerve surrounded by thick scar at level of lesion, hard neuroma on postero-lateral aspect. Ulnar nerve divided with gap	No relief of pain	27. 3.48	Pain with extrem... temperature. Not... no hyperalgesi... hyperaesthesia
	7.10.44	Post-ganglionic sympathectomy	Pain considerably relieved hyperalgesia persists in median area		

TABLE 2

CASE NO.	TYPE OF LESION	DATE OF INJURY	CLINICAL FEATURES: Time of onset of pain	Site of pain	Hand or foot temperature	Sweating	Date of examination	INVESTIGATIONS: Type
8	Median, Ulnar	14. 9.44	1st day	Hand	Warm	+	7 11 44	—
9	Median, Ulnar, Radial	14 11 44	1st day	Palm, especially ulnar area	—	—	2. 3.45 10. 3.45	Ulnar nerve block Paravertebral block
10	Brachial plexus	28. 4.44	4th week	Forearm, hand especially median area	—	—	—	Paravertebral block
11	Median, Ulnar	11 8 44	1st day	Hand, chiefly median area	—	0	26. 1 45	Paravertebral block Median nerve block
12	Median	14 12 43	1st day	Median area of hand	—	+	21. 4 44	Paravertebral block
13	Median, Ulnar	14. 6.42	2nd day	Medial border of forearm, palm of hand	Cold	++	9.11 43	Paravertebral block
14	Median (Inner head), Ulnar	23.11 44	1st day	Forearm, hand	Cold	+	9 2 46	Paravertebral block [illegible]
15	Median	22 11 44	2nd day	Forearm, median area of hand	—	—	—	Paravertebral block
16	Median	21. 4.45	—	Median area of palm and thumb	—	—	—	—

—(*continued*)

INVESTIGATIONS	TREATMENT			FOLLOW-UP	
Result	Date	Type	Result	Date	Result
—	12.11.44	Post-ganglionic sympathectomy (incomplete due to technical difficulties)	Some relief of pain, still severe hyperalgesia in median area		No follow-up (Germ P.o.W.)
	8.12.44	Neurolysis: median nerve thinned over distance 2 cm. No obvious intraneural scarring	Partial relief of pain and hyperalgesia		
Complete analgesia in ulnar area, pain diminished for 2 hr	23. 3.45	Post-ganglionic sympathectomy	Pain completely relieved	23. 1.48	No return of pain, though there is evide of regeneration of sympathetic fibres
Pain relieved for 2 hr					
Pain relieved for 1½ hr	16. 8.44	Post-ganglionic sympathectomy	Pain much better but still some burning pain in median area and hyperalgesia in median and ulnar areas	2. 4.45	No change in post-ope tive condition
Temporary relief of pain	3. 2.45	Sympathectomy attempted, not completed because of technical difficulties	Slight relief of pain hand still sweating		No follow up (Pol Army)
Pain relieved for 5 hr	7. 4.45	Neurolysis ulnar nerve soft neuroma found at point of exit from axilla	No appreciable effect on pain		
Partial relief of pain	22. 5.44	Neurolysis large soft neuroma on median nerve	No relief of pain	29. 1.48	Pain returned one y after sympathectomy with warmth and exc ment, but was not sev
	30. 7.44	Pre-ganglionic sympathectomy	Pain relieved, paraesthesia remained		
Pain relieved for 7 hr	3.10.45	Neurolysis neuroma involving ½ of nerve and a little extraneural scarring	No effect on pain	8.11.48	No return of pain up time of amputati Has phantom limb but this is not painf
	29.10.45	Pre-ganglionic sympathectomy	Relief on 10th post-operative day coincided with onset of sympathetic paralysis		
	9. 6.47	Amputation through forearm for joint contractures and residual palsy			
No effect on pain	8. 8.45	Exploration of plexus—median (latter head)-soft lateral neuroma involving ½ nerve. Ulnar- firm fusiform enlargement	Slight improvement in pain for 4 months	1. 2.50	No return of pain
	25. 3.46	Pre-ganglionic sympathectomy	Complete relief of pain		
Pain relieved for 30 min.	22. 1.45	Pre-ganglionic sympathectomy	Complete relief of pain on 5th post-operative day. No hyperalgesia	5.11.48	Complains of paraesthe in median distribu No real pain
—	4. 6.45	Pre-ganglionic sympathectomy	Pain relieved. Generalized hyperalgesia in palm and digits persisted for 2 months after operation	20. 4.46	No pain or hyperalges

TABLE 21

CASE NO.	TYPE OF LESION	DATE OF INJURY	CLINICAL FEATURES: Time of onset of pain	Site of pain	Hand or foot temperature	Sweating	Date of examination	INVESTIGATIONS: Type
17	Median, Ulnar	18. 6.44	1st day	All fingers and thumb but less severe in thumb and index finger	Warm	±	9. 8.44	Paravertebral block Oscillometry
18	Median, Ulnar, Radial	31.12.41	2nd week	Hand, chiefly median area	Warm	++	22. 1.42	Paravertebral block Median nerve block at wrist
19	Median, Ulnar, Radial	16. 3.44	1st day	Whole hand	Warm	±	1. 6.44	Paravertebral block (3 occasions)
20	Median, Ulnar* (sutured at time of injury)	2. 5.41	1st day	Wide median area in hand	No change	0	22. 5.41	Median nerve block at wrist
21	Median, Medial cutaneous	2.10.40	1st day	Hand and inner side of forearm	Cold	++	13. 3.41	Paravertebral block Brachial plexus block
22	Median	13. 2.45	3rd day	Hand, median area	—	—	—	Paravertebral block

—(*continued*)

INVESTIGATIONS	TREATMENT			FOLLOW-UP	
Result	Date	Type	Result	Date	Result
Pain relieved for 1 hr	4. 7.44	Removal of foreign body lying against ulnar nerve	No relief of pain		
Oscillations increased in affected forearm	2. 9.44	Neurolysis median nerve was involved in scar and had small lateral neuroma which was resected	Pain relieved for one day then returned to median area		No follow up
		Resection neuroma ulnar nerve anterior transposition and suture	No pain in ring and little fingers		
	2.10.44	Pre-ganglionic sympathectomy	Pain relieved. Still has hyperalgesia to pin-prick in median area		
Pain relieved for 10–15 min.		Exploration plexus and periarterial sympathectomy	Slight relief of pain for 3 to 4 days		
Pain in hand completely relieved	24. 3.42	Neurolysis median nerve, which was of normal appearance			
		Ulnar nerve, flattened grows intraneural scar ring. Suture performed			
	May 1942	Radiotherapy to hand	No immediate relief of pain	31. 5.44	Some weeks after therapy pain beg diminish. When la had no spontaneo
	July 1942	Radiotherapy to elbow and forearm			
Pain relieved for several hours on each occasion	Oct. 1944	Radiotherapy to hand and axilla	No immediate relief of pain but became less severe 3 weeks after treatment	8. 6.45	Pain much less, carries wet cloth pain becomes Touching dry still causes paroxy pain
Pain in hand relieved	28. 7.41	Neurolysis median and ulnar nerves. Nerves surrounded by dense scar some intraneural scarring of median, firm neuroma at level of suture of ulnar nerve	No relief of pain	31. 7.45	Spontaneous im ment of pain not months after Still had some p hand when fast especially in cold w
Not complete but considerable relief of pain and tenderness	7. 5.41	Neurolysis median nerve—which was slightly thickened and showed little intraneural scarring	No relief of pain	1. 7.42	Pain in cold o weather but n severe as when treatment
Partial relief of pain for 48 hr	9. 7.41	Periarterial sympathectomy	No relief of pain		
Some permanent alleviation of pain	17. 7.43	Neurolysis median nerve lateral neuroma densely adherent to surrounding scar	No relief of pain	26. 1.46	Pain improved fol two paravertebra pathetic blocks. S some pain whe charged
	June 1943	Radiotherapy	No relief of pain		

ntinued)

...STIGATIONS	TREATMENT			FOLLOW-UP	
Result	Date	Type	Result	Date	Result
—	17 8 40	Neurolysis, median and ulnar nerves grossly thickened and surrounded by scar	Temporary improvement in pain	18. 1.45	Still has some pain in t hand in hot and co weather and modera hyperaesthesia and hyperalgesia
lieved for 1½ hr	—	—	—	16. 8.46	Spontaneous improve ment at 5 months. N pain when last seen
ef of pain	21 10.44	Neurolysis, median and ulnar nerves intact and of normal appearance	No relief of pain	15. 4.46	Improvement noted at months. Still h twinges of pain w heat and emotion stimuli when last see
lieved for 1 hr	29 8.44	Neurolysis median nerve nerve normal appearance surrounded by dense scar	No relief of pain	24. 1 47	Some gnawing pain hand especially in co weather—not severe
elieved for 2½ hr	7 8.41	Neurolysis, median nerve embedded in dense scar tissue	Slight relief of pain for 24 hours.	1 12.44	Improvement in p noticed 2 years af injury Much bet when last seen, but had pain in hot weat
improved	1 10.41	Resection and suture of 6 cm. median nerve and 5 cm. brachial artery	Burning pain in median area considerably better but not completely relieved. No change in ulnar area		

(1) Case No 48 J B., aged 24 complained of constant burning pain in the dorsum of the foot and toes, following a bullet wound of the popliteal fossa on 26th April, 1943 Examination, two months after injury revealed slight power in the peronei and complete paralysis of the remaining muscles supplied by the lateral popliteal nerve. There was also some weakness of the intrinsic muscles of the foot and long flexors of the toes and partial loss of sensibility in the distribution of the lateral popliteal nerve. The pain was relieved for two hours by a procaine block of the lateral popliteal nerve where it crossed the neck of the fibula. At operation on 17th July the medial and lateral popliteal nerves were found to be surrounded by scar tissue and adherent to each other The scar tissue infiltrated the deep surface of the lateral popliteal nerve but the fibres going to form the sural nerve appeared healthy and were therefore preserved. The scarred segment of the nerve was resected and sutured. Following the operation the pain in the dorsum of the foot was abolished, but the burning pain persisted in the sural area.

(2) Case No. 27 E. S G., aged 40, was wounded in the upper arm by a bomb splinter on 29th May 1940 and sustained a lesion of the median, ulnar radial and musculocutaneous nerves. When examined at a *Nerve Injuries Centre* on 9th April, 1941 he was complaining of burning pain in all digits of the hand and especially in the index finger and thumb The pain was aggravated by physical and emotional stimuli. There was paralysis of flexor digitorum profundus, flexor pollicis longus, and the median intrinsic muscles of the hand, and weakness of the remaining muscles supplied by the median nerve and of all of those supplied by the ulnar There was intense hyperaesthesia and hyperalgesia in the sensory distribution of the median and ulnar nerves. Neurolysis was performed on 7th August, 1941, the median nerve being freed from a mass of dense scar tissue. The pain was not relieved by this procedure and on 8th October 1941 two and a half inches of the scarred median nerve was resected together

29

in cases of causalgia in the lower limb

INVESTIGATIONS	TREATMENT			FOLLOW-UP	
Result	Date	Type	Result	Date	Result
Pain completely relieved	6. 9 42	Neurolysis lateral popliteal nerve freed from scar: some intraneural fibrosis	Relief of pain for few days only		
Pain relieved, though sympathetic innervation of limb was not affected as there was no rise in T° of leg and normal sweating.	8.10.42	Resection and suture neuroma lateral popliteal nerve	Slight relief of pain for two days	31 7 45	No return of pain. Is working as postman for 8 hr day
Foot (sole) anaesthetic: no effect on pain	10. 5 43	Further neurolysis medial popliteal nerve adherent to lateral popliteal nerve and surrounded by scar. Further resection and suture neuroma lateral popliteal nerve	No relief of pain		
	19 11 43	Lumbar ganglionectomy (2,3,4)	Complete relief of pain and hyperalgesia		
Complete relief of pain. Some residual tenderness	20. 6.44	Lumbar ganglionectomy (2,3,4)	Complete relief of pain some tenderness remained in sole of foot	25. 4.45	No pain. Foot still very tender
Complete relief of pain for 4 hr Hyperalgesia much reduced.	12.11 40	Periarterial sympathectomy	No relief of pain		
	30. 7 41	Neurolysis medial popliteal nerve intact, extraneural scar constricting nerve	No relief of pain		
Complete relief of pain and hyperalgesia	17 9 41	Lumbar ganglionectomy (2,3,4)	Complete relief of pain and tenderness	13. 9 48	Patient has remained free of pain and hyperalgesia since sympathectomy
Foot hot, dorsum continued to sweat. Pain slightly relieved	Aug. 1947	Lumbar ganglionectomy (1,2,3)	Complete relief of pain and hyperalgesia	1 12.48	No recurrence of pain. Stroking sole of foot causes tingling
No relief of pain, still had some sensation in anterior part of sole and plantar surface of toes					
Complete pain relieved					
Pain abolished for 6 min.					
—	11 9 46	Lumbar ganglionectomy chain had plexiform arrangement. Only one large ganglion in front of body of L4	No pain, still has slight tingling in sole of foot	17 1 49	Numb pain in foot in cold damp weather. Some hyperaesthesia in sole of foot
Pain relieved for [illegible] days	30 5 45	Neurolysis sciatic nerve densely scarred on medial aspect, [illegible] of nerve intact	Temporary relief of pain worse 4 months later	2. 2.48	Some aching and burning pain in ankle when walking on hard pavements. Slight hyperaesthesia
	23. 1 46	Lumbar ganglionectomy (2,3 4)	Pain relieved. Hyperalgesia persists. Maximum effect 6 weeks after operation		

TABL

CASE NO.	TYPE OF INJURY	DATE OF INJURY	CLINICAL FEATURES					INVESTIGATION
			Time of onset of pain	Site of pain	Hand or foot temperature	Sweating	Date of examination	Type
34	Medial, Lateral } Popliteal	30. 9 42	1st day	Sole of foot	Warmer	±	4. 9 45	Sciatic nerve block to lesion Paravertebral bloc ? complete
35	Medial, Lateral } Popliteal	June 1940	?	Sole of foot	Cold	++	24 6.46	Paravertebral block Block repeated T.E.A chloride (slo started)
36	Posterior Tibial	17 5 44	1st day	Sole of foot	No change	++	27 2.45	Paravertebral block Post-tibial nerve b at ankle
37	Medial, Lateral } Popliteal	Jan. 1942	1st day	Foot chiefly sole	—	—	—	—
38	Medial, Lateral } Popliteal	9 7 44	1st day	Sole of foot	Cold	0	7 12.44	Paravertebral block
39	Medial, Lateral } Popliteal	25 6 44	1st day	Big toe and sole of foot	Cold	±	8. 1 45	Paravertebral block
40	Medial, Lateral } Popliteal	5 4.45	1st day	Medial border and dorsum of foot	—	—	—	—
41	Medial, Lateral } Popliteal	8. 4.45	10–12th day	Sole of foot and dorsal aspect of toes	No change	+	25. 5.45	Post tibial nerve bl at ankle
42	Medial, Lateral } Popliteal	24.10 42	During 2nd week	Ankle—whole of foot and toes	Warm	0	15.7 43	400 mgm. T.E A B
43	Medial, Lateral } Popliteal	24.10 42	1st day	Foot	—	—	—	Paravertebral block occasions)

—(continued)

INVESTIGATIONS	TREATMENT			FOLLOW-UP	
Result	Date	Type	Result	Date	Result
Some relief of pain for 3 weeks	Nov 1943	Neurolysis sciatic nerve, fusiform neuroma on medial popliteal division	No relief of pain	3.11 47	Still has jabbing pain in sole of foot with warmth and exercise. Patient was P.o.W for 2 yr
No relief of pain	Feb. 1944	Injection of 70 per cent alcohol into sciatic nerve above lesion	Pain much worse		
	1 4.46	Lumbar ganglionectomy (2,3,4)	Pain relieved, hyper algesia persists		
Incomplete no relief of pain Incomplete no relief of pain Sweating abolished pain greatly diminished	25. 4 47	Lumbar ganglionectomy (1,2,3).	Pain relieved also extreme hyperaesthesia and hyperalgesia	28. 4.48	Still complains of pain in foot and toes and there is slight hyperaesthesia and hyperalgesia (recurrence coincided with decrease of pension. Patient P.o.W for 5 yr.)
Pain relieved for one hour	Sept. 1944	Periarterial sympathectomy	No relief of pain		No follow up patient in Polish Army
No effect on pain	7 3.45	Lumbar ganglionectomy (2,3 4).	Pain relieved		
—	24. 4.46	Lumbar ganglionectomy (2,3 4)	Pain relieved and hyper algesia less pronounced	22.12.47	No recurrence of pain
Pain relieved for 20 min.	21 12.44	Lumbar ganglionectomy (probably 1 and 2). Some difficulty at operation	Pain relieved—sympathectomy complete	11 2.48	Free of pain—slight hyperaesthesia in foot
Pain relieved for 2 hr	1 2.45	Lumbar ganglionectomy (1,2,3)	Pain in foot relieved	12. 4.45	Foot still comfortable
—	17 6.45	Neurolysis sciatic nerve densely adherent to scar tissue at one point. No gross damage to nerve	No relief of pain	12. 9.47	No spontaneous pain—hyperaesthesia and hyperalgesia persist and cause considerable disability
	24. 7 45	Lumbar ganglionectomy	Marked relief of pain hyperalgesia persists in sole of foot		
Pain relieved temporarily although full anaesthesia of sole of foot was not obtained	29 5.45	Lumbar ganglionectomy (2,3 4)	Slight pain and tenderness lateral border of foot. Otherwise free of pain	14 10.48	No causalgic pain. Slight aching pain in foot after walking on hard pavements
Complete relief of pain for 2 3 hr	3. 4.43	Neurolysis sciatic nerve which was embedded in adhesions Small foreign body removed from nerve	Slight relief of pain	23. 2.49	Considerable spontaneous improvement in the causalgia but 6 yr after injury pain still troublesome complete relief obtained by a sympathectomy at this time
	6. 1 49	Lumbar ganglionectomy (1,2,3)			
After first block lost all pain and sensation in lower limb due to infiltration of somatic nerves 2nd and 3rd block no relief of pain		No operative treatment			Spontaneous relief of pain occurred over period of 18 months

TABLE

TYPE OF INJURY	DATE OF INJURY	CLINICAL FEATURES					INVESTIGATIONS
		Time of onset of pain	Site of pain	Hand or foot temperature	Sweating	Date of examination	Type
Medial / Lateral Popliteal	18. 9 44	During 2nd week	Heel and outer border of foot	Warm	—	24. 5.45	Paravertebral block, complete
Medial / Lateral Popliteal	30.1 44	2nd day	Sole of foot	—	—	—	—
Medial popliteal	22. 1 45	1st day	Arch and outer part of sole of foot	Warm	0	7 3.45	—
Medial / Lateral Popliteal	9 7 43	1st day	Sole of foot	Warm	0	23.11 43	Spinal anaesthetic Paravertebral block
Medial / Lateral Popliteal	26. 4.43	—	Dorsum of foot and toes	Warm	++	20. 6.43	Lateral popliteal block, neck of fibula Paravertebral block

with two inches of the brachial artery which had also sustained some damage. After the operation pain in the median area of the hand was partially relieved but the pain in the ulnar area was unchanged. The pain improved slowly over a period of years and when last seen in December 1944, the patient stated that the pain was much easier but became more severe during hot weather

(3) Case No 17 C. C., aged 31 was wounded in the upper arm by a mortar-bomb splinter on 18th June, 1944 sustaining a lesion of the median and ulnar nerves. The day following injury he complained of pain, "like severe toothache" in the palm and digits of the hand, less severe in the index finger and thumb, which was aggravated by coughing, sneezing, deep breathing and emotional stimuli. When examined seven weeks after injury he had great weakness of all the muscles supplied by the ulnar nerve and slight weakness of the median intrinsic muscles of the hand. Sensory testing was difficult but light touch appeared to be lost in the distribution of the median and ulnar nerves, and pinprick caused diffuse burning pain in the same area. At operation on September 2, 1944 the median nerve was freed from scar tissue and a small lateral neuroma was excised. There was a large neuroma on the ulnar nerve this was resected and a suture performed after anterior transposition. On the day following operation pain returned to the median area of the hand but was abolished in the ulnar area. Two months later the pain was completely relieved by a preganglionic sympathectomy

The interesting feature of each of these three cases is that resection and suture of the damaged portion of the nerve gave partial or complete relief of pain in its sensory distribution. The failure to secure complete relief was due to nerves

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...STIGATIONS	TREATMENT			FOLLOW-UP	
Result	Date	Type	Result	Date	Result
fect on pain	1. 8.45	Neurolysis sciatic nerve, no abnormality. Nerve surrounded by fine filmy adhesions	No relief of pain	6. 2.47	Steady spontaneous relief of pain but still present with heat and exercise. Hyperalgesia of sole of foot still troublesome
—	2. 8.44	Neurolysis sciatic nerve which was thickened and infiltrated with scar tissue and densely adherent to surrounding structures	No immediate improvement in pain	25. 8.47	Steady spontaneous relief of pain over period of 3 yr. Hyperalgesia of sole of foot still troublesome
—	13. 3.45	Neurolysis medial popliteal nerve and removal of small foreign body from nerve, which was thickened and adherent to surrounding tissue	Pain partially relieved	14. 7.47	Still some pain in foot, still has hyperalgesia in central part of sole of foot
...lieved immediate ...ore any evidence ...ck of pre-gangli- ...sympathetic fibres ...wn by loss of skin ...derable relief of	11. 1.44	Neurolysis sciatic nerve, involved in dense scar tissue. Large soft neuroma on lateral side, firm on medial side	No relief of pain	17. 4.44	Pain slightly better 3 months after operation. No further follow up
...lieved temporarily ...lieved temporarily	17. 7.43	Neurolysis medial popliteal nerve. Resection and suture neuroma on lateral popliteal nerve (fibres to sural nerve spared). Both popliteal nerves involved in scar and adherent to each other	Pain in dorsum of foot abolished, but pain persists in sural nerve area	15.10.46	Pain in sural area gradually subsided. No pain when last seen

being involved in pairs, or in one case, incomplete resection of all afferent fibres. These findings are in agreement with those of the Medical Research Council Report (1920) "Care must be taken that the ulnar nerve is not involved in scar even where causalgia appears to be of median origin only and internal saphenous where sciatic is at fault. Nerves are frequently injured in pairs and causalgia may be associated with all" The failure of resection and suture to relieve causalgia has often been cited as evidence in support of the theory that causalgia is caused by abnormal activity within the spinal cord (Livingston, 1943) This interpretation is not in accord with the clinical observations on the three cases here reported and will be discussed later

(iii) *Periarterial Sympathectomy*

This procedure, advocated by Leriche (1916) was employed on four occasions and in each case it failed to relieve the pain This is not surprising, as stripping the adventitia from an artery has purely local effects most of the autonomic fibres travel with the mixed nerves and are distributed to the arteries throughout the length and especially at the periphery of the limb

(iv) *Radiotherapy*

At one Centre radiotherapy was employed empirically in a number of cases. The technique used was that recommended by Mumford (1938) for "acute painful osteoporosis Seven patients with causalgia of the upper extremity were given four treatments of 150 Röntgen units to the painful area, at weekly intervals using a superficial therapy tube at 70 K.V Two patients had in addition a single dose of 800 R. units to the site of the nerve lesion In three patients there was no relief of pain in the remainder a little improvement was noted commencing three to six weeks after treatment, which may have been due to the radiotherapy or to spontaneous remission of the pain The results of radiotherapy compared so unfavourably with those of sympathectomy that the method was not given a prolonged trial

(v) *Sympathectomy*

Sympathectomy has now an established place in the treatment of causalgia and provided the cases for operation are carefully selected most patients obtain striking relief Before considering sympathetic denervation of the upper or lower limb it is wise to ascertain the response to procaine or other block of the appropriate sympathetic ganglia

In the upper limb it is necessary to infiltrate only the second thoracic ganglion, but it is usual to include the stellate since the appearance of Horner's syndrome is additional confirmation of a successful injection. In the lower limb it is usual to infiltrate the second third, and fourth lumbar ganglia. With practice these procedures are not difficult but the results must be interpreted with caution. A complete block of the sympathetic ganglia cannot be assumed unless there is complete anhidrosis of the limb and an appreciable increase in the warmth of the hand or foot These effects should appear within five to ten minutes of the injection It is also important to ascertain that the block is confined to the sympathetic ganglia, for somatic nerves may be infiltrated inadvertently the resulting anaesthesia of a part of the limb making the interpretation of the results unreliable.

A successful block of the sympathetic outflow to a limb often gave relief of pain for from one to three hours failure to secure any relief after two successful blocks was regarded as a contra indication to sympathectomy (Tables 30–31)

The potentialities of blocking of the sympathetic ganglia by tetra-ethyl ammonium bromide were not fully investigated as the drug became available only after the war Tetra-ethyl ammonium bromide was used twice, in doses of 300 and 400 mgm. and T E.A. chloride on one occasion—dose not stated All the patients were relieved of pain and one did not complain of its return until two to three hours after the injection. It is possible that the longer-acting methonium compounds now available may be even more valuable in the pre-operative investigation of cases of causalgia.

With three exceptions every patient benefited from a sympathectomy The failures were caused by technical difficulties during the operation and subsequent examination revealed that the sympathectomy was incomplete. The intervals between wounding and sympathectomy varied from five weeks to almost seven years. The long delay in securing treatment was due to the patients being held as prisoners of war but it did not prejudice the efficacy of sympathectomy

(*a*) *Upper extremity* (*Tables* 28 *and* 30 *pps* 164 *and* 180)

Two types of sympathectomy were performed (i) Cervico-thoracic ganglionectomy in which the lowest cervical and first, or first and second thoracic ganglia and intervening trunk are removed This operation a post ganglionic sympathectomy does not produce as effective vasodilation of the limb as the pre-ganglionic operation and gives the patient a Horner's syndrome. (ii) Pre-ganglionic sympathectomy (Smithwick 1940) in which the second and third thoracic ganglia are isolated by dividing the white rami communicantes to each ganglion and the sympathetic trunk below the third ganglion.

On theoretical grounds these two procedures should be equally effective in the relief of pain but in practice this was not the case. A number of completely satisfactory results were obtained with both operations but there were more failures with the postganglionic operation (Table 28)

Of the eighteen operations of both types three were failures and in each of them it was known that the sympathectomy was inadequate because of technical difficulties at the time of operation Six patients had a preganglionic sympathectomy and were completely free of pain following the operation four of the patients were also relieved of hyperaesthesia and hyperalgesia In one patient the pain returned with warmth and excitement one year after operation, and appeared to be due to regeneration of the sympathetic fibres.

Eight patients had a post ganglionic sympathectomy Three were completely relieved of spontaneous pain and hyperalgesia following the operation and remained so during the follow up period In the remaining five patients there was considerable but not complete relief of pain following the sympathectomy and in three of them the hyperalgesia persisted with its original intensity In one case no record was made of the type of sympathectomy

(*b*) *Lower extremity* (*Tables* 29 *and* 30 *pps* 172 *and* 180)

The results of sympathectomy were better in the lower limb than in the upper The operation consisted in the removal of the first, second and third or second, third and fourth lumbar ganglia, both being pre ganglionic sympathectomies Fifteen operations were performed all patients were relieved of pain initially but in four some pain returned during the first year after operation and six still had some hyperaesthesia and hyperalgesia in the sole of the foot which persisted for many months after the operation

Ulmer and Mayfield (1946) and White and Smithwick (1944) have suggested that the area of sympathetic denervation must reach well above the level of the nerve injury and that in wounds at the level of the knee joint the sympathectomy should include the first lumbar ganglion and in high lesions of the sciatic, the lowest thoracic ganglion The number of high lesions of the sciatic nerve in this series was too small to permit any conclusion on this point, but such evidence as there is does not support the contention of these authors. Furthermore, it is unlikely that many sympathetic fibres to the *thigh* are conveyed by the sciatic nerve, and it seems probable that the occasional failure of a lumbar ganglionectomy to relieve causalgia may be attributed to anomalies in the sympathetic outflow to the lower limb

Analysis of the 33 sympathectomies shows that a pre ganglionic is superior to a post-ganglionic operation in the treatment of causalgia, which is the view of Rasmussen and Freedmann (1946) No satisfactory explanation was found for the superiority of the pre-ganglionic operation or for the partial failure of

TABLE 30

Analysis of results of sympathetic ganglion block and of sympathectomy

Case no	Type of lesion	Effect on pain	
		Sympathetic ganglion block	Sympathectomy
1	Median, Ulnar, Radial	Relief	Complete relief
2	Median, Ulnar	Relief	Relief apart from aching in heads of metacarpals
3	Median, Ulnar	Relief	Complete relief
4	Median	Relief	Relief for 3 months, then moderate relapse
6	Median, Ulnar, Radial	Relief	Spontaneous pain relieved for 8 months hypersensibility persisted
9	Median, Ulnar, Radial	Relief	Complete relief
10	Brachial plexus	Relief	Partial relief
11	Median, Ulnar	Relief	0
12	Median	Partial relief	Pain relieved some return 1 year later Paraesthesia persisted
13	Median, Ulnar	Relief	Complete relief
14	Median, Ulnar	No relief (?) inadequate	Complete relief
15	Median	Relief	Complete relief but paraesthesia 3 years later
17	Median, Ulnar	Relief	Relief of pain hyperalgesia persisted
18	Median, Ulnar, Radial	Relief (15 minutes)	0
19	Median, Ulnar, Radial	Relief	0
21	Median	Partial relief	0
22	Median	Partial relief	0
24	Median, Ulnar, Radial	Relief	0
25	Median, Ulnar, Radial	No relief probably inadequate	0
26	Median, Ulnar	Relief	0
27	Median, Ulnar, Radial	Relief	0

TABLE 30 (*continued*)

Case no.	Type of lesion	Effect on pain	
		Sympathetic ganglion block	Sympathectomy
28	Medial, and lateral popliteal	Relief	Complete relief
29	Medial, and lateral popliteal	Relief	Complete relief of pain some residual tenderness in sole of foot
30	Medial popliteal	Relief of pain hyperalgesia reduced	Complete relief
31	Medial, and lateral politeal	Relief (tetra-ethyl ammonium bromide)	Complete relief
33	Medial, and lateral popliteal	Relief	Spontaneous pain relieved. Pain on walking on hard surfaces
34	Medial, and lateral popliteal	No relief probably inadequate	Spontaneous pain relieved hypersensibility persisted
35	Medial, and lateral popliteal	No relief undoubtedly inadequate, later great relief after tetra-ethyl ammonium chloride	Spontaneous pain relieved some pain 1 year later
36	Posterior tibial	Relief	Complete relief
38	Medial, and lateral popliteal	Relief	Spontaneous pain relieved slight hyperaesthesia of foot 3 years later
39	Medial, and lateral popliteal	Relief	Complete relief
42	Medial, and lateral popliteal	Relief (tetra-ethyl ammonium bromide)	Complete relief
43	Medial, and lateral popliteal	No relief	0
44	Medial, and lateral popliteal	No relief (?) inadequate	0
47	Medial, and lateral popliteal	Considerable relief	0
48	Medial, and lateral popliteal	Relief	0

0—Sympathectomy not performed

TABLE 31

Summary of results of sympathetic ganglion block

Nature of block	Pain		
	Relieved	Partially relieved	Unrelieved
Complete	27	4	1
Probably inadequate	—	—	4

some of the sympathectomies, for no detailed investigations were made of residual vasomotor and sudomotor activity following operation.

In some patients the hyperalgesia persisted although there was complete relief of spontaneous pain The persistent hyperalgesia was presumably caused by an irritative lesion of the somatic sensory fibres at the site of the nerve injury rather than by an inadequate sympathectomy

6 Pathogenesis

In spite of many investigations into the cause of causalgia the problem still remains an enigma, for none of the theories at present in vogue explain all the observed facts.

Most workers agree that sympathectomy will relieve the pain in most cases and it is tempting to attribute the relief of pain to the abolition of afferent pain impulses transmitted by the sympathetic nervous system (Bingham, 1948) There are, however serious objections to this hypothesis. It is impossible to demonstrate any change in sensibility in a limb which has been sympathectomized for peripheral vascular disease, and lesions of the cauda equina are encountered from time to time in which the spinal nerves are damaged below the level of the sympathetic outflow to the lower limbs, yet in spite of the normal sympathetic innervation there is complete loss of sensibility

In two patients a low spinal anaesthetic was administered with the object of blocking the sensory afferent fibres from the limb while sparing the sympathetic connexions

(1) Case No 47 Patient A T had severe causalgia following a sciatic nerve lesion at the level of the buttock Three and a half c.c. of 5 per cent procaine were injected into the spinal theca with the patient sitting. There was immediate relief of pain long before the pre-ganglionic sympathetic fibres were paralysed, for there was no rise in the skin temperature of the big toe as measured by a thermocouple until eight minutes after the administration of the anaesthetic.

(2) Case No 28 Patient T P had severe causalgia following a lesion of the medial and lateral popliteal nerves in the popliteal fossa Procaine (1 c.c.) was injected into the spinal theca and complete anaesthesia was obtained up to the level of the third lumbar dermatome. The pain in the foot was abolished but the sympathetic outflow to the lower limb was unaffected as there was no rise in the skin temperature of the first and fifth toes.

From these observations it is reasonable to assume that the pain impulses are conveyed centrally by somatic sensory fibres and not by the sympathetic nervous system These impulses cannot originate in the afferent sensory fibres since the pain is relieved by a procaine or chemical block of the sympathetic ganglia, which has no effect on the sensory fibres (see Tables 30 31 pps. 180, 181) It must be assumed, therefore, that sympathectomy acts by blocking efferent impulses passing along the sympathetic fibres which in some way stimulate sensory fibres at the site of the nerve lesion or at the periphery

During waking hours there is a constant stream of efferent autonomic impulses which is increased by a wide variety of physical and psychic stimuli, such as excessive heat or cold a painful stimulus applied to any part of the body loud noises emotion and excitement deep breathing, physical exertion, and many other forms of stimulation whereas sleep greatly reduces the activity of the autonomic centres in the hypothalamus. The patient is caught in a "cycle of peculiar viciousness, pain and worry leading to sympathetic discharge, causing further pain and worry" (Doupe, Cullen and Chance, 1944) from which relief is sought by sleep or by avoiding all forms of psychic and physical stimulation, until such time as relief is obtained by sympathetic denervation

It is now necessary to consider how the efferent impulses in the sympathetic fibres stimulate the somatic afferent nerves. Doupe *et al* (1944) believe that fibre interaction may occur at the site of the nerve lesion or at the nerve endings. Granit *et al* (1944) have shown that an artificial synapse between motor and sensory fibres can occur at the cut end of a nerve or even after a nerve injury which does not stop conduction to the periphery Although these workers did not demonstrate interaction between the sympathetic and sensory fibres there is no reason to suppose that it does not occur

Causalgic pain cannot, however be explained solely on the basis of an artificial synapse between sympathetic and sensory fibres at the site of the nerve lesion for resection of the damaged segment of nerve has often failed to relieve causalgia, though it must eliminate both the afferent and efferent arcs of the short-circuited area The failure may be due to inadequate resection, or more likely as in the three cases reported previously to the pain being associated with a lesion of more than one nerve A graver objection is that causalgic pain following a lesion of one nerve is sometimes relieved by blocking the nerve with procaine distal to the lesion. This observation led Doupe and his co-workers to postulate a distal causalgic syndrome in which the conjunction of the sympathetic and sensory fibres occurred at the periphery when their nutrition was impaired by oedema or ischaemia They produced no evidence to support this hypothesis and it could hardly explain those cases of causalgia in which the pain began within a few hours of injury

In these patients there was always an incomplete lesion of the median or medial popliteal nerves or their roots or branches and most workers agree that causalgia rarely occurs when a nerve is completely divided It seems probable, therefore that in most cases the preservation of distal conduction is essential to the development of the syndrome. If the artificial synapse between the sympathetic and sensory fibres occurs at the site of the nerve lesion which is the only reasonable possibility it must be assumed that this causes antidromic impulses to pass down the sensory fibres, and that these impulses cause the release of a pain producing substance at the periphery of the limb or in some way lower the threshold of stimulation of the sensory nerve endings.

Lewis (1937) has shown that when the distal end of a divided nerve is stimulated the skin it supplies becomes flushed and warm and that this may be accompanied by burning pain in the skin. The pain impulses reach the central nervous system through adjoining nerves, the territories of which overlap that of the affected nerve, for Foerster has shown that the pain is abolished by section of the adjoining nerves. This so-called antidromic vasodilation is thought to be due to the release of vasodilator products peripherally The response to antidromic stimulation is very similar to that seen in some cases of causalgia. A criticism of this analogy is that all cases of causalgia do not show vasodilation, but it is not established that antidromic vasodilation can be maintained indefinitely without compensating factors intervening disuse will cause a large measure of cooling, and pain is known to cause vasoconstriction

The clinical features of causalgia and the satisfactory response to sympathectomy can be explained on the basis of the following hypothesis. The lesion is usually caused by the passage of a missile in the vicinity of the nerve which results in a stretch injury without solution of continuity of the nerve or permanent loss of conductivity The injury breaks down the insulation of the nerve fibres and an artificial synapse is established between the efferent sympathetic and afferent sensory fibres Impulses passing down the sympathetic fibres are

short circuited to the sensory somatic fibres where they travel both centrally and distally (antidromic) The antidromic impulses cause a vasodilator substance to be released at the periphery This substance either reduces the threshold of sensory stimulation or may itself set up centripetal impulses in the sensory fibres which summate with the centripetal impulses arising directly at the artificial synapse (Fig. 130)

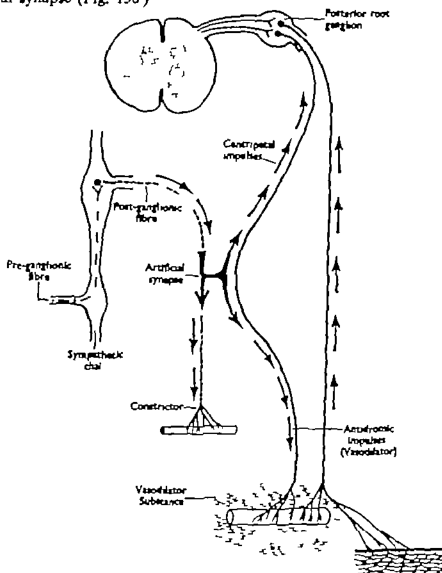


FIG 130. Diagram of pain pathways in causalgia.

On this hypothesis a sympathectomy would relieve the pain if it completely abolished all the efferent impulses travelling by the sympathetic fibres. Lewis (1942) suggested that sympathectomy relieved the pain by improving the peripheral circulation and washing away the pain producing vasodilator substances at the periphery The objection to this concept of the modus operandi of sympathectomy is that reflex vasodilation produced by heating the unaffected limbs does not relieve causalgic pain

The hypothesis also explains the variable response to a nerve block distal to the lesion. A successful nerve block abolishes the antidromic impulses and the centripetal pain impulses arising at the periphery of the limb If these impulses

are responsible for most of the pain considerable relief may be expected from the distal nerve block on the other hand it will have little or no effect if the pain is caused chiefly by centripetal impulses arising at the artificial synapse

Causalgia is usually associated with lesions of the median or medial popliteal nerve, which is not surprising as these nerves carry most of the sympathetic fibres to the hand and foot the remaining fibres are conveyed mostly by the ulnar and lateral popliteal nerves. Causalgia is often associated with lesions of both median and ulnar nerves in the upper and the medial and lateral popliteal nerves in the lower limb For this reason section of one nerve either proximal or distal to the lesion may fail to relieve causalgic pain completely

The time of onset of causalgia is very variable, and may be related to the duration of the loss of distal conduction resulting from the nerve injury Once the pathway is established pain persists until such time as there is effective insulation of the fibres at the site of the nerve lesion which would arrest the passage of impulses across the artificial synapse, or until the efferent impulses in the sympathetic fibres are abolished by sympathectomy

7 Summary

(1) Forty-eight cases of causalgia are reviewed and the clinical features are described

(2) Causalgic pain usually has a burning quality and is most severe in the hand and foot. It is aggravated by both physical and emotional stimuli

(3) The pain usually begins during the first few days after injury and rapidly reaches a climax It may persist unabated for many months but most cases show a tendency to spontaneous improvement over a period of years

(4) The sudomotor and vasomotor changes are variable. The glossy skin, stiff joints, wasted finger pads and the generalized osteoporosis in the affected limb are not characteristic of causalgia itself They appear to be related to disuse of the painful extremity

(5) Multiple nerve injuries are commonly present and causalgia may be associated with all In the upper limb there was always an incomplete lesion of the lower trunk or inner cord of the brachial plexus or of the median nerve, and in the lower an incomplete lesion of the medial popliteal nerve, or of the medial popliteal division of the sciatic, or of the posterior tibial nerve. These nerves carry most of the sympathetic fibres to the hand and foot. With two exceptions all the nerve lesions were at or above the level of the knee or elbow joint.

(6) Sympathectomy gives marked relief of pain in most cases of causalgia. Prompt treatment is essential to prevent the crippling deformities which follow prolonged immobilization of the painful limb The results of pre-ganglionic are superior to those of post-ganglionic sympathectomy

(7) The results of other methods of treatment are presented and discussed

(8) The current theories on the pathogenesis of causalgia are examined and it is concluded that the most satisfactory hypothesis is as follows

As a result of the nerve lesion an artificial synapse is established between sympathetic and somatic afferent nerves Efferent impulses streaming down the sympathetic fibres are short-circuited to the sensory fibres and there pass both centrally and distally (antidromic) The antidromic impulses cause the release of a histamine like substance at the periphery which either reduces the threshold of sensory stimulation or itself causes pain impulses in the sensory fibres, which summate with the centripetal impulses arising directly at the artificial synapse.

V

NEUROVASCULAR LESIONS

by R. L. Richards

1 General Introduction, Material and Classification

At certain levels in the limbs the anatomical proximity of nerves and blood vessels makes it inevitable that many perforating or penetrating wounds will injure both The effects of such injuries are complex and depend to a great extent upon the relative importance of the nerve and vascular lesions. The vascular disturbances which follow uncomplicated injuries of peripheral nerve have been discussed in Chapter I but, before proceeding further with a discussion of neurovascular lesions it is necessary to emphasize that an arterial injury alone may result in "lessened functional capacity (of a limb)—the latter manifested in lowering of the common sensation the incidence of subjective sensations and loss of muscular power progressing to paresis or actual paralysis" (Makins, 1919). Thus in a sense every arterial injury may be considered as a neurovascular lesion but for the purposes of this report the term will be applied only to cases in which there was definite evidence of an injury to both nerve and blood vessel or in which as a result of an arterial injury there was some persisting interference with nerve function

Some wounds of this type so seriously impair the viability of the limb that immediate or early amputation is necessary The observations which follow refer therefore only to those cases in which the injured limb survived for at least some weeks after wounding.

For the purpose of this section the records of some 4 000 patients from three Peripheral Nerve Injury Centres were used and the medical history of every patient who was suspected of having a neurovascular lesion was scrutinized.

For many reasons it is exceedingly difficult to obtain accurate data on the incidence of combined injuries of nerves and blood vessels. In the case of major vessels such as the common femoral or subclavian it is relatively easy to decide whether the vessel has been injured but with smaller vessels the evidence is much more difficult to obtain. At a primary wound toilet a surgeon may tie a large bleeding vessel, in the arm for example, feel reasonably certain that he has tied the brachial artery and record that fact on the patient s field medical card Some weeks later when the patient is examined at a Peripheral Nerve Injuries Centre it may be possible to feel the brachial artery pulsating immediately above, below and even across the wound track Conversely there may be no record of a vascular injury on the patient s case notes, but on clinical examination at a later date pulsation may be absent in a major vessel With still smaller vessels such as the radial the ulnar or the tibial vessels records are even more unreliable. Nevertheless, lesions of even these vessels may be significant in the pathogenesis of a nerve lesion and they must be considered. For the purposes of the present study the following were accepted as evidence of vascular injury

(1) The presence of an aneurysm or of an arteriovenous fistula.

(2) Absence of pulsation in major vessels proximal to and including the brachial artery at the elbow and the popliteal at the knee.

(3) A record of an artery having been ligated or seen divided or thrombosed, and absence of pulsation in that artery distal to the level of injury

(4) Ocular evidence of division or thrombosis of an artery at a second operation

(5) A record of arterial spasm substantiated by clinical evidence of ischaemia

(6) An arterial lesion demonstrated by arteriography

(7) Pathological evidence of muscle or nerve ischaemia even in the presence of normal arterial pulsation and without a history indicating direct vascular injury

Using these criteria, 243 cases of combined neurovascular injury were obtained from the records 183 lesions in the upper limb and 60 in the lower Tables 32 and 33 show the incidence and distribution of the combined neurovascular lesions from two of three centres concerned Both centres dealt with a

TABLE 32

Neurovascular lesions Upper limb

Artery	Nerve	Series A	Series B	Total
Subclavian	Brachial plexus	1	1	2
Thoraco-acromial axis	Brachial plexus	0	1	1
Axillary	Brachial plexus	4	8	12
	Median and ulnar	1	0	1
	Median and musculo-cutaneous	1	0	1
	Radial	3	0	3
	Median	1	0	1
	Ulnar	0	2	2
Brachial	Median, ulnar radial and musculo-cutaneous	1	1	2
	Median, ulnar and radial	4	7	11
	Median and radial	1	0	1
	Median and ulnar	11	13	24
	Median and musculo-cutaneous	0	1	1
	Radial	1	2	3
	Median	6	15	21
	Ulnar	3	2	5
Profunda brachii	Radial median and ulnar	1	0	1
Radial and ulnar	Median and ulnar	1	4	5
	Median and posterior interosseous	0	1	1
	Median	2	2	4
	Ulnar	0	1	1
Radial	Median	4	4	8
	Ulnar	1	0	1
Ulnar	Median, ulnar and posterior interosseous	1	0	1
	Median and ulnar	0	1	1
	Median	1	1	2
	Ulnar	4	6	10
Anterior interosseous	Median	1	0	1
	Totals	54	73	127

TABLE 33

Neurovascular lesions Lower limb

Artery	Nerves	Series A	Series B	Total
Internal iliac	Sciatic	0	1	1
Superficial femoral	Medial and lateral popliteal	1	7	8
	Lateral popliteal	0	1	1
	Saphenous	1	0	1
Profunda femoris	Medial and lateral popliteal	2	0	2
Popliteal	Medial and lateral popliteal	3	5	8
	Anterior tibial	0	1	1
Posterior tibial	Posterior tibial	4	8	12
	Lateral popliteal	0	1	1
	Medial popliteal	1	0	1
	Lateral popliteal and posterior tibial	1	0	1
	Anterior and posterior tibeal	0	1	1
Anterior tibial	Anterior tibial	1	2	3
	Lateral popliteal	0	1	1
Anterior and posterior tibial	Anterior and posterior tibeal	1	1	2
	Totals	15	29	44

total of approximately 1 100 patients with nerve injuries, but the centre from which Series B was obtained was particularly concerned with injuries of blood vessels as well as with those of peripheral nerves, and the staff were therefore on the lookout for vascular injuries hence no doubt the higher incidence in that series This is a further indication of the difficulties which arise in any attempt to obtain accurate data on the incidence of such lesions.* Although the data obtained are therefore considered valueless from a statistical standpoint, they are presented to indicate the criteria used and the material which was available for study The figures confirm the impression that combined injuries of nerves and blood vessels are more frequent in the upper limb a finding which is readily explained by the closer anatomical relationships of the main nerves and blood vessels in the arm as compared with the thigh and by the relatively greater mass of muscle in the latter

Theoretically neurovascular lesions may be divided into two main groups (1) those in which there is evidence of direct injury to both nerves and blood vessels at the time of wounding, and (2) those in which the evidence indicates that blood vessels alone were injured and the nerve lesion can be regarded as secondary to the vascular lesion, that is due to ischaemia, pressure from an aneurysm, etc In practice there are only a few clear-cut cases which can be

* Lyons and Woodhall (1949) state that injury of a major vessel was present in 12·9 per cent of the cases of nerve suture reported to the U.S Peripheral Nerve Registry

allocated with certainty to one or other of these groups the majority present features which would entitle them to be placed in both

The simplest type of neurovascular lesion occurs when a wound causes division of a nerve and an adjacent blood vessel for example the median nerve and brachial artery at the elbow Spontaneous closure of the divided vessel follows, or it is ligated at the primary operation of wound toilet. A few weeks or months later when the wound is healed the nerve is explored and resection and suture are performed In such a case the vascular lesion has little if any effect upon the prognosis as far as recovery of the nerve is concerned

Most of the 243 cases mentioned above are of this favourable type and need not be considered further This section will be devoted to a discussion of those cases in which the vascular lesion was considered to play a major part in the clinical picture presented. For convenience the cases will be considered under the following headings

Syndrome of Ischaemic Paralysis
- (A) Due to open wounds
- (B) Associated with closed fractures
- (C) Due to other causes

Traumatic Aneurysms and Peripheral Nerve Injuries

2. Syndrome of Ischaemic Paralysis

INTRODUCTION

In his book on "Nerve Wounds" Tinel (1917) devotes a chapter to Ischaemic Paralysis of the Upper Limb" but he alone among those who wrote about peripheral nerve injuries during and after the First World War appears to have realized that there was a distinct syndrome of ischaemic paralysis. His description of the condition is excellent and a summary of his observations provides a good introduction for this section.

The condition usually follows obliteration of a large artery such as the subclavian axillary or brachial but is also found occasionally after lesions of smaller arteries. The mechanism is far from clear because some patients with arterial wounds develop ischaemic paralysis and others with apparently identical wounds do not the development of a collateral circulation is obviously the deciding factor Two phases of the condition are described First, a stage of oedematous infiltration of the ischaemic regions. The hand is cold cyanosed or reddish ("the colour of lees of wine) soft swelling affects all tissues and they have a "pasty" feel Active movements are slight and passive movement possible but resisted There is a tendency to hyperaesthesia with hyperalgesia to certain forms of stimuli a sense of deep pain of a burning or freezing type is experienced and the hand is kept covered. If sensation is carefully tested the loss is found to be "vaguely segmental The second stage is a fibrous transformation of the infiltrated tissues. The oedema subsides and leaves a fibrous mass the muscles harden and develop a wooden feel the skin becomes smooth and shiny tends to ulcerate readily and heal slowly and the nails are talon like. Active and passive movements disappear and as loss of sensation becomes complete, pain disappears. The hand is gradually transformed into a sort of fibrous, rigid inert and insensitive appendage " Tinel does not mention ischaemic paralysis of the lower limb but, as will be shown below the syndrome is also observed following wounds of the femoral and popliteal arteries.

Considering the problem from the vascular rather than the neurological viewpoint, Makins (1919) in his monograph "On Gunshot Injuries to the Blood Vessels" described a similar condition as occurring "in the most unfavourable class of case, short of early massive gangrene

Although these descriptions make it clear that ischaemic paralysis was recognized during the war of 1914–18 it was not until recent years that the effect of vascular lesions upon the peripheral nerves was fully appreciated.

Jefferson (1934) and Leriche (1940) described the consequences of sudden arterial obstruction the symptoms and signs were elegantly summarized by Jefferson as pain, pallor paralysis and absence of pulsation. After about 15 minutes the fingers or toes feel numb then the sense of touch, followed by that of heat and cold, is lost, and at 20 to 25 minutes there is loss of sensibility extending as high as the leg or the forearm at about the same time muscular weakness develops, starting in the thenar muscles and spreading centripetally to affect the interossei, flexors and extensors in that order at one hour paralysis is complete up to the elbow or knee. If at this stage, the circulation is restored, complete or almost complete recovery will follow but if not, function is definitely lost and death of tissue occurs. Depending upon the period that elapses before the collateral circulation becomes efficient, one of four results may follow (1) massive gangrene of the limbs (2) patchy necrosis of muscle and peripheral gangrene, (3) ischaemic sclerosis, (4) or a limb which has a barely adequate circulation at rest so that it is cold and cyanotic, shows nutritional changes in the skin and its appendages, and develops intermittent claudication on exercise The syndrome of ischaemic paralysis includes cases belonging to the second and third of these categories.

In clinical practice the effects of sudden arterial occlusion are seen in their purest form in cases of embolism. Griffiths (1940) described three cases of ischaemic paralysis following arterial embolism and showed that the clinical picture in these cases was indistinguishable from that seen in classical Volkmann's ischaemic contracture. This was one of the reasons which led him to conclude that the latter condition was due to arterial injury with spasm of the collateral circulation The evidence as far as the peripheral nerves were concerned was taken a stage further when Holmes, Highet and Seddon (1944) showed that the nerve lesions in cases of Volkmann's ischaemic contracture were due to the effects of ischaemia (p 134)

Since 1940 a number of reports have appeared in the literature of cases in which nerve lesions were directly attributable to an arterial injury Leriche (1941) described the case of a man with a wound of the subclavian vessels which he explored 19 hours after wounding. He found the brachial plexus intact but the subclavian artery had been contused and was thrombosed the damaged segment of artery was removed. Before the operation weakness of the interossei and hypoaesthesia of the entire hand and forearm were noted *after the operation* there were signs of interference with the functions of the ulnar median and musculo-cutaneous nerves which recovered spontaneously over a period of three months. Parkes (1945) in a paper on traumatic ischaemia of peripheral nerves described six cases of gunshot wounds involving the main arteries of the limbs. These cases have been included in the present series Wertheimer (1946) reported three cases in which nerve lesions were associated with vascular injuries at operation the nerves were found undamaged but arterial lesions (thrombosis in two cases and an aneurysm in the third) were present. In the cases of thrombosis, resection of the damaged artery was followed by improvement, but

in the case of aneurysm the paralysis was increased post-operatively In their Atlas of Peripheral Nerve Injuries Lyons and Woodhall (1949) presented the histological findings in two cases of ischaemic paralysis of the upper limb

A ISCHAEMIC PARALYSIS DUE TO OPEN WOUNDS

In the present series there were 34 cases of ischaemic paralysis resulting from open wounds in 19 of these the lesion was in the upper limb and in 15 the lower limb was affected The following are two typical cases

Case 13 J B., age 20 sustained a bullet wound of the right upper arm on June 16 1944 The limb immediately felt numb and dropped to his side he was unable to move the hand Considerable bleeding from the wounds took place and he applied his field dressing. His wounds were later dressed at a field surgical unit and he was given one pint of blood. Anti-gas-gangrene serum, penicillin and sulphadiazine were administered but he had no further local treatment for his wound. On June 19 "numbness and paralysis of biceps, triceps, brachioradialis and extensors" was noted The following day his hand was swollen and absence of the radial pulse was recorded. On June 24 dry gangrene of the tip of the middle finger was noted. On June 28 he was found to have an audible systolic bruit over the brachial artery at the level of his wounds. This persisted for five days and was heard by several independent observers, but thereafter disappeared. At about this time he was found to have a complete radial and median palsy but the ulnar nerve was thought to be intact. The first detailed neurological examination was made on July 17 and he was then found to have complete lesions of the median, radial and musculo-cutaneous nerves, but the ulnar nerve was not interrupted. The radial pulse at the wrist and the brachial pulse at the elbow could not be felt An area of superficial necrosis was present on the tip of the middle finger (Fig. 131) The radial pulse was first felt on August 10 and a week later was of good volume. On August 25 the first dorsal interosseous and flexor-pronator muscles were thought to feel unduly firm and a supination contracture of the forearm with flexion contracture of the fingers were present. There was now a delayed, diffuse and very unpleasant response to deep pin-prick over the cutaneous distribution of the median nerve. For the next three months there was no improvement in the functions of the median nerve, but the radial nerve showed both sensory and motor recovery On November 15 the median nerve was explored and found to be in continuity with only a small lateral neuroma on the antero-medial surface. One month later the patient was discharged from the army and the hospital, and unfortunately further examinations could not be made.

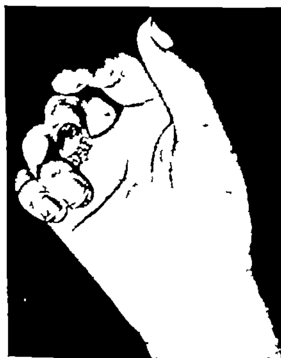


FIG 131 Case 13 Superficial necrosis of tip of middle finger

In those cases where injury to a major vessel was not followed by isch a collateral circulation adequate for the needs of the distal tissues mu *become established within a relatively short time of wounding.* The factors control the development of collateral circulation are as yet unknown b fundamental necessities are the opening up of vessels which are to ca auxiliary blood supply and a blood pressure in the limb high enough to m an adequate blood flow through these vessels In the case of a wounde these factors may be interferred with by either the general or local effects wound The presence of a large wound or multiple wounds may cause oli shock with a fall in blood pressure and blood volume and peripheral constriction three factors which will interfere materially with the develo of a collateral circulation A large destructive wound may destroy not on main vessel but also important branches which, with a smaller wound, be spared to take part in an adequate collateral circulation. Should the w of the main vessel result in a large haematoma, this may compress imp collaterals. Local interference with collateral channels may also be d multiple wounds in the limb or to external pressure from injudicious pa tight bandaging, plaster casts or the prolonged application of a tourniqu

The records of the 34 cases in this group were therefore studied for ev of any of the following

(1) A large destructive wound
(2) The presence of a large tense local haematoma
(3) Large blood loss or shock.
(4) Injury to or pressure upon, collateral vessels.
(5) Mention of traumatic arterial spasm

In only three of the 34 cases was none of these factors recorded, and in than one third of the cases (12) two or more of the factors were pr (Table 36)

TABLE 36

Incidence of factors interfering with development of collateral circulatio

Factor	No. of cases
Large destructive wound	11
Tense local haematoma	9
Large blood loss	17
Traumatic arterial spasm	5
Interference with collaterals by	
(*a*) Direct injury	3
(*b*) Application of tourniquet	4
(*c*) Pressure from packing or plaster	2

Further evidence that an adequate circulation did not develop in these c in which ischaemic paralysis resulted was obtained by a study of the condi of the peripheral pulses, the radial pulse in the upper limb and the poste *tibial pulse* in the lower limb. Following* a straightforward ligation of brachial or axillary artery the radial pulse commonly returns within a few d

* The posterior tibial pulse was chosen in preference to the dorsalis pedis as the latt absent in 12 per cent of normal men.

and is usually of good volume by 14 days. In the lower limb the posterior tibial pulse is usually a little longer in returning, but four to six weeks after the ligature of the popliteal or superficial femoral artery it may be felt quite readily (Makins, 1919 personal observation) In Table 37 which follows the condition of the peripheral pulse in the 34 cases in the present series is recorded In most of the cases the observation recorded is that made at the time of the initial examination at the Nerve Injuries Centre, but in the few cases in which the patient was admitted to a centre shortly after wounding, either the date of return of the pulse is recorded or if the pulse had not returned up to three months, it is recorded as being absent at that time.

TABLE 37

Condition of peripheral pulse

Case no	Pulse	Months since wounding	Case no	Pulse†	Months since wounding
	Upper limb			Lower limb	
1	0	3	20	1	5
2	2	6	21	1	11
3	0	3	22	0	5
4	2	5	23	0	5
5	2	1	24	NR	5
6	1	4	25	3	12
7	1	3	26	0	5
8	1	7	27	0	4
9	0	6	28	2	3
10	0	6	29	3	2
11	1	6	30	0	10
12	1	3	31	0	10
13	2	4	32	0	4
14	1	6	33	2	3
15	1	3	34	0	22
16	2	7			
17	2	7			
18	0	3			
19	0	4			

Arbitrary pulse notation
0 = absent
1 = doubtful or very faint
2 = diminished, weak or poor
3 = normal
4 = full, bounding

Radial at wrist. † Posterior tibial behind malleolus.

In 23 of 34 cases the peripheral pulse was *absent or doubtfully present at an average period of six months after wounding*. In the remaining ten cases in which there was a record of the peripheral pulses, a fair or good pulse had returned at an average period of five months after wounding. Perhaps the most significant fact that can be elicited from the data in Table 37 is that in only four cases had a definite pulse returned in three months or less from the date of wounding.

These results afford strong presumptive evidence that in the majority of cases ischaemia is the result of an impaired collateral circulation. Factors which operate at the time of injury and immediately thereafter result in an inadequate blood flow through collateral vessels, with the result that thrombosis occurs in distal vessels, and even if the adverse factors are later corrected the return of circulation is delayed the clinical evidence of this delay being the absence or poor quality of the peripheral pulse months afterwards

(ii) *Nerve Lesion*

The nerve lesion must be considered from several aspects first, the clinical picture secondly the findings at operation in those cases in which exploration was performed thirdly the pathological findings where available and finally from these and other data an attempt may be made to determine the pathogenesis of the nerve lesion in each case and to prove the contention that ischaemia was a major factor

(*a*) *Findings on clinical examination* For present purposes it is necessary to consider only the broad outlines of clinical findings interpreted in terms of nerve function Later sections will deal with motor and sensory findings in more detail The state of the injured limb at three to six months after wounding was chosen as the basis for the clinical assessment of nerve function since it was felt that at this period any transient interference with nerve function should have recovered, while recovery due to regeneration of interrupted axons should not have progressed very far The distribution of the nerve lesions was considered first (Table 38)

TABLE 38

Distribution of nerve lesions

Nerves involved	No of cases
Brachial plexus	3
Median, ulnar radial and musculo-cutaneous	2
Median, ulnar and radial	12
Median and ulnar	2
Total	19

In the cases in which the lower limb was affected both divisions of the sciatic nerve were involved in every case.

When the nerve lesions were assessed in terms of the completeness or otherwise of the interruption of function, the following results were obtained. There were three brachial plexus lesions Cases 1 and 9 were generalized plexus lesions with complete paralysis of the forearm and hand, and Case 7 was diagnosed clinically as having a complete lesion of the lateral cord

The results in the other cases are shown in Table 39

In the upper limb the picture presented was very similar in most of the cases It will be seen from Table 38 that 12 of the patients presented lesions of the median, ulnar and radial nerves, and that in another two the musculo-cutaneous nerve was affected also All these patients had comparatively severe interference with the functions of the median and ulnar nerves, but as regards the radial

TABLE 39

Assessment of nerve function

Nerve	Lesions		Total
	Complete	Incomplete	
Median	12	4	16
Ulnar	9	7	16
Radial	2	12	14
Medial popliteal	4	11	15
Lateral popliteal	5	10	15

nerve the lesion was a paralysis of the thumb extensors and occasionally the finger extensors, usually without any loss of sensibility in the distribution of the superficial radial nerve. There is a strong probability that this paralysis of distal radial muscles was due as much to ischaemia of the muscles themselves as to interference with nerve function In two cases, however there was a complete radial palsy distal to the branches to triceps

In the lower limb the clinical picture in most of the cases was similar there was paralysis below the knee with the gastrocnemius and sometimes the peronei escaping, and a stocking or slipper distribution of sensory disturbance. In two cases, however there was a complete sciatic palsy

(*b*) *Findings at operation* An exploration of one or more of the injured nerves was performed in fifteen upper limbs and nine lower limbs The three brachial lesions were all explored with the following results

Case 1 Inner head of median divided.

Case 7 Lateral cord divided.

Case 9 Medial portion of inner cord damaged

The results of the other 21 explorations are summarized in Table 40

TABLE 40

Findings at operation

Nerve	Complete division	Injured	Normal	Total explored
Median	8	1	3	12
Ulnar	4	1	5	10
Radial	1	0	7	8
Medial popliteal	0	0	9	9
Lateral popliteal	0	0	8	8

Thus in quite a high proportion of the lesions in the upper limb and in all those in the lower limb the affected nerves were found to be normal when explored at the site of injury That the median nerve should have been found completely divided more frequently than any of the other nerves in the upper limb is not altogether surprising in view of the fact that a lesion of the main

blood vessel was present in all cases and the median nerve has closer anatomical relationships with the axillary and brachial arteries than either of the other two major nerves.

Before considering the pathological findings it is of interest to attempt to correlate the clinical and operative findings (Table 41)

TABLE 41

*Correlation of clinical and operative findings**

Nerve	Clinical findings		Operative findings		
	Complete	Incomplete	Divided	Injured	Normal
Median	9	3	8	1	3
Ulnar	6	4	4	1	5
Radial	1	7	1	0	7
Medial popliteal	4	5	0	0	9
Lateral popliteal	5	3	0	0	8

In the upper limb 13 of the 16 complete lesions that were explored were associated with complete division of the nerve, and two of the three remaining nerves were in continuity but damaged, in one case so badly that resection and suture was performed In the lower limb on the other hand, there were nine nerves in which the clinical findings indicated complete interruption but operation revealed a normal nerve

(c) *Pathological findings* Material for pathological examination was obtained from the following sources

1 In all the cases in which resection and suture was performed the resected portions of the proximal and distal stumps or the damaged portion of nerve were examined histologically
2. In four cases portions of nerve were removed as a biopsy
3 In two cases the nerves were examined following amputation of the limb in one case after an early amputation and in the other after a delayed amputation.

It is known that severe ischaemia produces certain characteristic changes in nerve (p 118) In the portions of nerve removed at the site of injury at the time of resection and suture there was no evidence of any ischaemia of nerve The appearances of the two stumps were in every case consistent with the degree of local injury which the nerve had sustained at that level.

The findings in the biopsy specimens and those obtained from the two amputated limbs are summarized in Table 42.

In only one case in the group therefore, was definite histological proof of nerve ischaemia obtained This is not as surprising as it may appear as a nerve biopsy perhaps more than any other type of biopsy consists of a piece of tissue chosen at random and frequently has, of necessity to be taken from a portion of nerve that is least likely to show the change

* Only cases in which data were complete are included in this Table, so that the figures do not correspond to those in Table 34

In the remaining cases a presumptive diagnosis of nerve ischaemia was made upon an assessment of all the clinical findings and since this included information obtained from the condition of the muscles, the sensory disturbances the nutritional state of the limb and the progress of the case a final discussion on the nature of the nerve lesion must be left until later

TABLE 42

Pathological findings

Case no.	Nerves examined	Report on histology
1	Dorsal branch of radial Dorsal cutaneous of ulnar	Wallerian degeneration partial re innervation. No evidence of ischaemia
2	Median at wrist (funicular biopsy) Dorsal branch of ulnar	Denervated and re innervated. No collagenisation Increased endoneurial collagen. Schwann tubes restricted
10*	Radial nerve Ulnar nerve Median nerve at wrist	Well re innervated with myelinated fibres As radial Very few myelinated fibres, numerous non-myelinated fibres
20	Lateral popliteal nerve (funicular biopsy)	Degenerated and re-innervation proceeding. No characteristic ischaemic changes
22	Lateral popliteal nerve (funicular biopsy) Musculo-cutaneous	Normal nerve Denervated. No evident ischaemia
24†	Sciatic nerve Lateral popliteal nerve Anterior tibial nerve Posterior tibial nerve	Normal apart from some reduction in no of fibres and myelin sheaths Denervated but no evidence of ischaemia

* Amputation 51 months after injury
† Amputation 9 months after injury

(iii) *Muscles*

It is well known that ischaemia of muscle may be diagnosed clinically During the acute phase which follows injury ischaemic muscles often appear rather swollen and the skin over them may be reddened as though indicating inflammation Passive movements which stretch such muscles cause severe pain Later the "muscles harden and develop a wooden feel which is quite characteristic Muscles affected by ischaemia do not at least at first waste as rapidly as denervated muscles and a paralysed muscle which is not wasted and feels somewhat firmer than normal should always be suspected of being ischaemic.

In 23 of the cases in the present series a clinical diagnosis of muscle ischaemia was made. The distribution of the ischaemia is shown in Tables 43a and 43b.

TABLE 43a

Muscle ischaemia—Clinical findings Upper limb

Case no	Triceps	Biceps	Extensors	Flexors	Intrinsics
2	−	−	−	+	+
3	−	+	+	+	+
4	−	−	−	−	+
5	−	+	+	+	+
7	−	+	−	−	+
9	+	−	−	−	+
10	−	−	+	+	+
11	−	+	+	+	+
12	−	−	+	+	−
13	−	−	−	+	+
15	−	−	−	+	−
16	−	−	−	+	+
17	−	−	−	+	−
18	−	−	+	+	+
19		+	−	+	+
	1	5	6	12	12

* In Cases 1 6, 8 and 14 there was no record of muscle ischaemia

TABLE 43b

Muscle ischaemia—Clinical findings Lower limb

Case no	Calf and posterior tibial	Anterior tibial
20	+	+
22	−	+
23	−	+
26	+	+
28	+	−
29	+	+
32	−	+
33	+	+
Totals	5	7

In Cases 21 24 25 27 30 31 and 34 there was no record of muscle ischaemia

In those cases in which a definite clinical diagnosis of muscle ischaemia was not made, two findings were frequently recorded which raised the suspicion that ischaemia might be an important factor in the pathogenesis of the paralysis. The first of these was the presence of more pronounced wasting than might have been expected from the nerve lesion alone and the second was a severe degree of

TABLE 44

Muscle ischaemia—Pathological findings

Case no.	Muscle examined	Findings
2	Pronator teres 4th dorsal interosseous	Normal muscle Macros. ischaemic Micros. fibrosis but no necrosis
5	Pronator quadratus	Ischaemic
7	2nd dorsal interosseous	Ischaemic
8	Pronator teres Pronator quadratus	Normal muscle Fibrous replacement, ? due to inflammation
10	Biceps Flexor-pronator group Abductor min. dig.	Denervated Denervated Partly denervated partly ischaemic
11	Biceps	Ischaemic—short head only
12	Extensor dig. communis	Ischaemic
16	Flexor-pronator group	Ischaemic
18	Flexor-pronator group	Ischaemic
19	Flexor-pronator group Abductor min. dig.	Denervated Denervated
20	Peronei	Ischaemic
22	Anterior tibial group Extensor dig. brevis	Ischaemic Denervated
23	Anterior tibial group	Ischaemic
24	Calf Flexor dig. longus	Ischaemic Ischaemic
26	Calf	Ischaemic
27	Calf Flexor dig. longus	Ischaemic Ischaemic
29	Soleus Anterior tibial group Flexor dig. longus Flexor hallucis longus	Normal Ischaemic Normal Ischaemic

contracture leading to a deformity which frequently required an operation to correct it. In 27 of the cases (17 upper limbs, 10 lower limbs) contractures were recorded as the cause of grave disability In the upper limb the characteristic contracture affected the pronators wrist and finger flexors and intrinsic muscles of the hand the deformity being one of pronation of the forearm, flexion of the wrist, flexion of the fingers and adduction of the thumb with flexion of the terminal phalanx (Fig. 133) In the foot the contracture was usually of the calf muscles and toe flexors, producing an equinus deformity with clawed toes (Figs. 140 143) Such deformities occur in neglected cases of peripheral nerve injury uncomplicated by ischaemia, but there is no doubt that in ischaemic paralysis they are more frequent, more severe and tend to occur even when the patient is receiving adequate supervision and treatment.

Clinical experience leads to a relatively high degree of accuracy in the diagnosis of muscle ischaemia, but, to be certain, pathological confirmation is advisable. In 17 cases in the present series specimens of muscle were examined either macroscopically or microscopically or both These specimens were obtained either by a deliberately planned muscle biopsy (7 cases) at operation (8 cases) or from an amputated limb (2 cases) The characteristic macroscopic and microscopic changes seen in ischaemic muscles have been described by Griffiths (1940) and Parkes (1945) The results of the biopsies are shown in Table 44 and illustrated by Figs. 134 and 135

Comparison of Tables 43a 43b and 44 will show that biopsies were available from two cases (8 and 27) in which ischaemia was not recorded clinically In Case 8 biopsy specimens were taken from the pronator muscles when these were divided in an attempt to overcome a severe contracture of the forearm The specimen from pronator teres showed normal muscles, but that from pronator quadratus revealed extensive fibrosis of the muscle which in the opinion of the pathologists suggested a chronic inflammatory process rather than ischaemia. In Case 27 the clinical state of the leg muscles was not recorded but after amputation necrosis of the calf and posterior tibial group of muscles was discovered. It will be further noted that in some cases (2, 10 19) muscles which were thought clinically to be ischaemic were found to be normal or only denervated on biopsy Since a biopsy consists of a small piece of muscle selected at random from the muscle belly unless the latter is wholly necrotic it is quite possible that the sample will not reveal the true picture in the greater part of the muscle

(iv) *Sensory Findings*

(a) *Subjective* Pain was the only important subjective sensory disturbance in these cases. The incidence of pain is indicated in Table 45

TABLE 45

Incidence of pain

Site of lesion	Pain				
	Severe	Moderate	Slight	None	No record
Upper limb cases	3	6	2	8	—
Lower limb cases	3	2	3	5	2
Totals	6	8	5	13	2



FIG 133 Case 15 Flexion contracture of digits.



FIG 134 Case 5 Muscle biopsy from biceps brachii photomicrograph shows necrotic muscle being replaced by scar tissue.



FIG 135 Case 29 Muscle biopsy from flexor hallucis longus, obtained 18 months after injury photomicrograph shows completely necrotic muscle with dense scar tissue at the periphery

Thus pain was a symptom in rather more than half the cases, and in a fifth it was severe. This is undoubtedly a higher incidence than would be expected in a series of uncomplicated peripheral nerve injuries. The type of pain experienced by the 19 patients is of some interest in eight it was described as burning or was associated with a sensation of heat four patients complained of *aching or gnawing pain* and in seven the pain was described as sharp shooting stabbing like needles etc. In all except one case the pain was felt either in the hand and fingers or in the foot and toes and appeared to be deep and not superficial pain. The exception was a patient who complained of a deep-seated burning pain in the forearm (Case 19) In one case (Case 6) a diagnosis of causalgia had been made before the patient reached a peripheral nerve centre and two months after wounding sympathectomy had been performed with considerable relief In the remaining cases the pain subsided spontaneously in from three weeks to ten months from the date of wounding The average duration of pain in the thirteen cases in which data were available was 3 5 months. It is improbable that ischaemia was the only cause of the pain in these cases, but it can be said that in both quality and distribution the pain was similar to that observed in other types of case in which ischaemia is known to be responsible for the pain, e.g. cases of occlusive vascular disease.

(*b*) *Objective* From the sensory findings made at the time of the first detailed neurological examination at a peripheral nerve centre the cases can be divided *into two groups*

(1) Those cases in which the area of sensory loss corresponded to the anatomical distribution of one or more peripheral nerves. Thirteen of the 34 cases belong to this group. In eight of these the nerves of the upper limb were affected and in five the sciatic nerve or its branches. In these cases there wa nothing in the distribution of the sensory loss to indicate the nature of the nerv lesion.

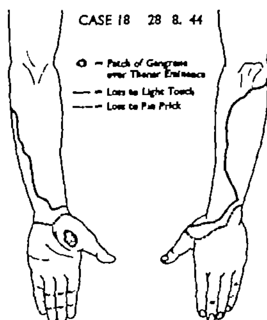


FIG 136 Case 18 Area of sensory loss note glove area of analgesia.

(2) Those cases in which the sensory loss was, as Tinel put it vaguely segmental There were 21 cases in this group eleven with upper limb lesions and ten with lesions in the lower In these cases the area of cutaneous sensory loss tended to be of glove or gauntlet type in the upper limb (Fig. 136) and of stocking sock or slipper type in the lower (Figs 137 and 138)

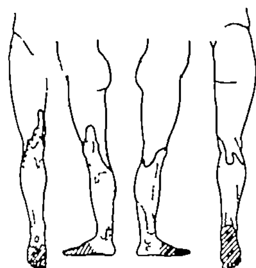


Fig 137 Case 25 Sensory findings note tendency to stocking distribution of anaesthesia

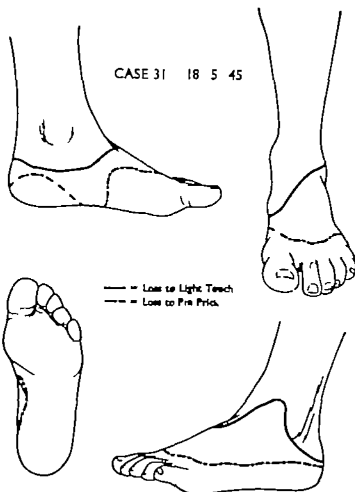


Fig. 138 Case 31 Showing carpet-slipper type of sensory loss.

As regards the quality of the sensory disturbance in the 34 cases there were one or two findings which supported the hypothesis that ischaemia was responsible In most of the cases belonging to the second group the boundaries of the loss to light touch and pin-prick were either co-terminous or else the area of analgesia was the greater In those cases in which the loss of sensitivity was not complete, it was found that what was preserved was a delayed, unpleasant, and very diffuse response to pin-prick or to pressure. Neither of these findings can be regarded as pathognomonic of ischaemic paralysis, but it is known from the experimental work of Lewis and Pochin (1938) and Weddell, Sinclair and Feindel (1948) that ischaemia is one of the possible causes of these effects.

(v) *Nutrition of Limb*

The nutrition of the muscles has been discussed above and this section will deal with the nutrition of the skin and subcutaneous tissues. Gangrene was recorded in seventeen cases in the series, i e. 50 per cent. In most of these seventeen cases, the gangrene consisted only of superficial necrosis of the tips of digits (Figs. 131 139 140 143) and rarely resulted even in the loss of the affected digits no amputations of fingers were performed and only three cases required amputation of toes. In one case a large area of superficial necrosis formed over the thenar eminence (Fig. 141) and in another the heel was the site of a similar area of necrosis. Fourteen patients, seven with lesions in the upper limb and seven with lesions in the lower had persistent trouble with ulcers and minor injuries to the extremities which were reluctant to heal Oedema was recorded in nine of the 19 cases in which the upper limb was affected as has already been stated (p. 36) oedema is rarely seen in cases with uncomplicated nerve lesions in the upper limb Swelling was a problem in all except two of the cases with involvement of the lower limb In all except five of the cases the nutritional changes which follow injury to a peripheral nerve (see Chapter I) were most conspicuous and the most severe degrees of digital atrophy alterations in nail growth and changes in the skin which were encountered were observed in the cases which are included in this group of ischaemic paralysis (Fig. 142)

The most severe nutritional disturbance observed was in a boy (Case 10) aged eight, who sustained an accidental bomb wound of the axilla which injured the four major nerves and contused the axillary artery (Fig. 132, p 193). Twenty four hours later the damaged segment of artery was excised At first the nutrition of the limb was very precarious, but eventually only the tip of the little finger was lost (Fig 139) After muscle biopsies had shown that only the small muscles of the hand were partially ischaemic, the nerves were sutured. Although relatively good nerve regeneration took place, the limb failed to grow a severe contracture of the forearm muscles developed and the nutrition of the hand was always a matter of concern to the boy and his parents Fifty-one months after the injury the limb was amputated.

As far as is known the upper limb was amputated in only one other case an officer (Case 16) received a wound in the lower third of the arm which severed the brachial artery and median and ulnar nerves. In spite of prompt and efficient surgical treatment, a severe contracture of the forearm muscles rapidly developed When he arrived at a Nerve Injuries Centre in the United Kingdom, the flexor pronator group of muscles was completely necrotic and was being discharged piece meal through a sinus in the mid forearm The nutrition of the hand was so precarious that even the pressure of a light padded splint caused ulceration (Fig. 142) Although the injured nerves had been repaired 15 weeks



FIG 140. Case 32. Appearance of foot 2 months after injury note necrosis of toes 3, 4 and 5 and severe clawing of toes.



FIG. 141 Case 18. Appearance of hand one month after injury note patch of necrosis over the thenar eminence.



FIG 142. Case 16. Showing severe nutritional changes in all digits and marked flexion contracture. Superficial ulceration on dorsal aspect of fingers caused by light padded splint.

after wounding, it was considered that even if nerve regeneration took place the functional result could be not other than poor and so amputation was advised and accepted

Two lower limbs were amputated (Cases 24 and 26) In both of these cases the indication for amputation was a fixed equinus deformity of an insensitive foot, the nutrition of which was too bad to sustain the strain of weight bearing.

It is thus apparent that in this group of 34 cases the incidence of nutritional disturbances was high and that in many oedema, ulcers and gangrene were a source of worry both to the patients and to those concerned with their welfare

(vi) *Treatment*

The important factors in treatment are the prevention of ischaemia if that is possible and if it is not, the correct management of the limb during the period of acute ischaemia. Once ischaemic paralysis has developed, it is irreversible and in most cases all that can be done is to treat the nerve lesions as in an uncomplicated case and to attempt to improve the function of the limb by splintage, physiotherapy and if necessary reconstructive operations If the clinical findings indicate that a nerve or nerves are completely interrupted they should be explored without delay the lesions are usually situated proximally

in the limb and if signs of recovery are awaited valuable time may be lost. Details of the nerve explorations which were performed in this series of cases have already been given (p 198) After the onset of ischaemic paralysis efforts to improve the collateral circulation by sympathectomy are not successful In this series of cases a preganglionic sympathectomy for the upper limb was performed in three (in one case primarily on account of causalgic pain) and a lumbar ganglionectomy for the lower limb in two cases. In none was there any evidence that the operations resulted in improvement in the nutrition of the



FIG 143 Case 31 Condition of foot 10 months after injury note loss of tip of great toe and little toe and clawing of toes 2, 3 and 4 (See p. 206).

limb Persistent and intensive physiotherapy is probably the most important factor in the treatment of established ischaemic paralysis and the patient must be trained to be exceptionally careful not to injure the insensitive limb with its impoverished blood supply It has already been mentioned that in many of these cases contractures develop even in spite of good supervision and care. In the lower limb these can be successfully corrected by operation, but in the upper limb the results are not encouraging. Operations were performed on the lower limb in four cases (lengthening of tendo Achillis, transplantation of toe flexors to extensors, etc.) with good results. Reconstructive operations on the

upper limb were performed in three cases, but in all the results were disappointing.

(vii) *Prognosis*

Three limbs were amputated within six months of wounding (see above) Of the remaining 31 cases, 28 have been followed for periods ranging from one to five years and from these some assessment of the prognosis in cases of ischaemic paralysis may be made. The data for these 28 cases are presented in Tables 46a and 46b The standard gradings for the assessment of recovery after nerve suture were found unsatisfactory and hence simpler methods have been adopted these are explained in foot notes to the tables.

Viewing the results as a whole it can be said at once that in most cases the prognosis is poor In the upper limb only two of 14 patients recovered any useful function in the small muscles of the hand, and only five recovered tactile sensibility in the hand. On the whole sensory recovery was a little better than motor One reason for this undoubtedly was the presence of ischaemic muscles

TABLE 46a

Recovery—Upper limb cases

Case no.	Follow-up (months)	Recovery		Function of limb
		Motor	Sensory	
1	28 (26)	Good	Fair	Good
2	50 (37)	Poor	Poor	Fair
3	60	Poor	Poor	Fair
4	57 (51)	Poor	Poor	Fair
5	42	Poor	Good	Fair
6	60	Fair	Fair	Poor
8	60	Good	Good	Good
9	44	Poor	Poor	Poor
10	51 (47)	Fair	Fair	Poor
11	60	Poor	Poor	Poor
14	60	Poor	Fair	Poor
15	50	Poor	Poor	Poor
17	50 (43)	Poor	Poor	Poor
18	60	Fair	Fair	Fair
19	60	Poor	Poor	Poor

Figures in brackets indicate interval after suture

Motor Recovery Poor—recovery in long muscles only
Fair—recovery in long muscles plus some activity in small muscles of hand
Good—recovery in long muscles plus some useful activity in small muscles of hand

Sensory Recovery

Sensibility in hand only
Poor—recovery of deep pain sensibility only
Fair—recovery of superficial pain and some recovery of tactile sensibility
Good—recovery of pain and tactile sensibility with loss of over reaction

Function of Limb This is largely a personal assessment of the usefulness of the limb to the patient and in making it several factors in addition to neurological recovery were considered.

Case 7—*Brachial* plexus lesion which could not be assessed under the above scheme
Cases 12, 13—No follow-up
Case 16—Limb amputated.

TABLE 46b

Recovery—Lower limb cases

Case no.	Follow up (months)	Recovery		Function of limb
		Motor	Sensory	
20	60	Poor	Fair	Fair
21	43	Good	Fair	Good
22	41	Good	Fair	Good
23	20	Fair	Fair	Good
25	31	Good	Fair	Fair
27	12	Poor	Poor	Poor
28	42	Good	Good	Good
29	52	Fair	Good	Good
30	28	Poor	Fair	Fair
31	40	Poor	Fair	Fair
33	36	Fair	Fair	Good
34	29	Good	Poor	Good

Motor Recovery Poor—no effective recovery in either calf or dorsiflexors of ankle
Fair—ability to plantar flex *or* dorsiflex the foot against slight resistance
Good—ability both to plantar flex and dorsiflex the foot against resistance

Sensory Recovery Grading as for upper limb but sole of foot considered
Cases 24 26—Limbs amputated
Case 32—No follow-up

which even when re innervated could not function. As far as the usefulness of the limb was concerned the results in the upper limb were bad in only two cases was the function of the limb considered good The results in the lower limb were a little better seven out of 12 patients had good limbs, that is they were adequate for weight bearing and walking and did not cause the patient any trouble on account of nutritional lesion only one patient had a limb whose function was considered poor' that is he would have been better with a prosthesis.

A large number of factors contribute to these poor results, but peripheral ischaemia is undoubtedly the most important. The pathological changes which take place in nerves, muscles joints and skin and its appendages as a result of ischaemia present formidable obstacles to be overcome by the already complex processes of nerve regeneration and functional recovery

(viii) *Conclusions*

If the series of cases is considered as a whole, it is apparent that the effects of the vascular lesion were predominant Whatever the nature of the lesion of the main artery the clinical picture was that of a limb with a barely adequate blood supply and in some cases with necrosis of muscle and/or skin and subcutaneous tissue. With regard to the nerve lesions the cases may now be divided into three groups

(i) *Those in which the nerves were known to be undamaged at the level of the wound* (14 *cases*). It is almost certain that the nerve lesions in this group were entirely due to ischaemia

(ii) *Those in which the state of the nerve at the site of injury was not ascertained* (9 *cases*) The clinical picture in these cases did not differ from that seen in the first group Furthermore the main reason why the nerves were not exposed was because it was considered improbable that they could have been directly injured It is therefore probable that the nerve lesions in this group also were largely if not entirely due to ischaemia

(iii) *Those in which the nerves were known to have been damaged by the missile* (11 *cases*) Therefore the nerve lesions could not be due to ischaemia alone but there is good evidence that ischaemia was a significant factor in all of them The incidence of muscle necrosis and peripheral gangrene was as high in this group as in the other two and the degree of recovery in the sutured nerves was poor It is in this group also that the only positive biopsy for nerve ischaemia was obtained (Case 2, Table 42, p 199)

Therefore in all gunshot wounds of the limbs in which there is evidence of damage to both nerves and blood vessels the possibility that the nerve lesion is due to the vascular injury should be considered. Clinical findings which favour the diagnosis of ischaemic paralysis are a poor or absent peripheral pulse, paralysed muscles which feel abnormally firm severe contracture, sensory loss which is vaguely segmental and the presence of marked nutritional changes including patchy peripheral gangrene. Surgical exploration of the nerves at the site of wounding, biopsy of suspected muscles and in selected cases, nerve biopsy may all help to confirm the diagnosis.

B ISCHAEMIC PARALYSIS ASSOCIATED WITH CLOSED FRACTURES

The occurrence of ischaemic paralysis in association with a closed fracture has been recognized as a clinical syndrome for many years. The classical type is that originally described by von Volkmann in 1872 and which now bears his name. Within recent years, the work of Griffiths (1940) and others has added considerably to our understanding of the pathogenesis of Volkmann s ischaemic contracture It is now generally accepted that this syndrome is usually if not always, the result of an arterial injury complicating the fracture.

In the present series there were a number of cases of ischaemic paralysis associated with closed fractures Some of these were of the classical Volkmann type—ischaemic paralysis complicating a supracondylar fracture of the humerus others were associated with fractures of other bones of the upper limb or with fractures in the lower limb These cases will not be considered in detail in this report first because many of them have already been described by Holmes Highet and Seddon (1944) and Parkes (1945) and secondly because in most cases the features of the paralysis were identical with those already discussed in this chapter

The following case record illustrates most of the typical features of the group

Case 35 A 24-year-old marine was injured on July 11 1944 when the ship in which he was serving struck a mine and blew up He sustained a closed fracture of the head of the left tibia with an effusion into the knee joint. Impaired circulation in the left foot was noted within a few hours of injury but it was said to have improved after reduction of the fracture. Three days later the patient was admitted to a Nerve Injuries Centre He was complaining of severe pain in the injured limb the foot and leg were grossly swollen, the foot was cold and cyanotic, active movements of the toes and ankle were absent, sensation was lost as high as mid-calf and the popliteal, posterior tibial and dorsalis pedis pulses were absent. An emergency operation was performed. The popliteal artery was exposed and found to be in spasm. It was dissected free for several inches and after a few moments pulsation in the vessel returned and the pulses in the foot could be felt. At operation the sciatic nerve and both its divisions were seen to be intact and macroscopically normal. The nutrition of the foot improved steadily following the operation, but a complete sciatic palsy persisted (Fig. 144) This was observed over a

period of three years and during that time a fair degree of recovery of sensibility but very little motor recovery took place. The latter was undoubtedly due to the condition of the muscles which were wasted and clinically fibrosed. The nutrition of the foot remained good and the posterior tibial and dorsalis pedis pulses were of good volume. As a result of the precarious condition of the limb in the acute stage, the fractured tibia was allowed to unite with some deformity and the knee joint was unstable. On account of these disabilities and the lack of recovery in the muscles below the knee, the limb was amputated (elsewhere) 38 months after the injury Unfortunately histological studies were not made.



FIG 144 Case 35 Condition of left le fter injury, note deformity of knee joint, wasting of leg muscle foot and clawing of t

The typical features of this group marized as foll

(i) *Fracture*

The fracture is n the e elbow or pra condylar fracture rus, e hildren an f the head of the tibia y liabl cated by is lysis.

The syndrome may also follow other fractures in the present series ischaemic paralysis was seen in association with a fracture-dislocation of the shoulder transverse fractures of both bones of the forearm, a fracture of the lower end of the ulna, a fracture-dislocation of the wrist joint, a fracture of the femoral shaft at the junction of the middle and lower thirds and transverse fractures of both bones of the leg

(ii) *Arterial Lesion*

In the acute stage the presence of an arterial injury may be suspected from symptoms and signs of impaired peripheral circulation at or shortly after the time of injury These all important manifestations are spontaneous pain in the injured limb which is greater than would be expected as a result of the fracture alone, pain on passive stretching of muscles (usually the finger flexors or calf muscle) pallor (more often than cyanosis) of the hand or foot, swelling (not invariably) and most important of all absence of the peripheral pulse (the radial at the wrist or the posterior tibial pulse at the ankle)

If these symptoms and signs persist or develop following efficient reduction of the fracture, exploration of the artery at the level of the fracture should be performed and in most of the cases reported in the literature an arterial lesion (spasm, contusion, thrombosis or rupture) has been found

When ischaemic paralysis is fully developed, clinical signs of peripheral ischaemia may be absent or difficult to detect, as in the case quoted above, but in many cases absent or diminished peripheral pulses persist, oscillometry reveals diminished excursions in the injured limb distal to the level of injury and nutritional disturbances in the hand or foot are greater than might be expected as the result of the nerve lesions only At this stage arteriography may reveal that the artery has been damaged at the level of the fracture.

(iii) *Nerve Lesion*

The presence of a lesion of a peripheral nerve or nerves is an integral part of the syndrome of ischaemic paralysis complicating a closed fracture. Clinically many different forms of nerve lesion are encountered. Occasionally the findings may be those of complete interruption of a single nerve (as in Case 35 above) More frequently two or more nerves are involved e g. median and ulnar nerves, and the picture may be either that of complete loss of function or of partial loss of function affecting chiefly the distal branches of the nerves On the motor side the degree of nerve damage is often difficult to assess because of muscle ischaemia it is not easy without the aid of electrical reactions, electromyography or muscle biopsy to decide which muscles are ischaemic and which are denervated On the sensory side the areas of sensory disturbance often show a tendency to be of the glove gauntlet, carpet-slipper or sock distribution, and in the less severe cases some pain sensibility with a delayed and very unpleasant type of response (so-called protopathic pain') may be preserved

The pathology of these nerve lesions was the subject of detailed investigation by Holmes, Highet and Seddon (1944) Prior to their work it had been accepted that the nerve lesions were due either to direct trauma at the time of injury or to compression of the nerves by the fibrosed ischaemic muscles. In some cases the first of these factors was undoubtedly operative, but it had long been known that in many cases exploration of the nerves at the level of the fracture either did not reveal any evidence of damage or else the damage was much less than had been expected from the clinical findings. Despite such encouraging findings

at operation, the degree of recovery in the nerve lesions was almost invariably poor Seddon and his colleagues were able to demonstrate that, irrespective of the presence or absence of damage to the nerves at the fracture site, profound macroscopic and microscopic changes could be found in the nerves where they traversed the region of greatest muscle ischaemia (Fig. 145) The histology of ischaemic nerve is discussed elsewhere in this report (p 134) but it is appropriate to describe here the macroscopic appearance of nerves as seen at exploration in cases of ischaemic paralysis. This is perhaps best done by quoting the findings of Holmes, Highet and Seddon in one of their cases

Case 2. A case of ischaemic paralysis complicating a fracture of the mid-shaft of the left humerus.

"At exploration at level of fracture median and ulnar nerves appeared normal and were *not involved in scar tissue. Median nerve and its branches of normal consistency and diameter* (6 mm.) as far as 6 cm. below medial epicondyle. Nerve passed between the deep and superficial heads of pronator teres but there was no sign of constriction. Below this level the nerve gradually narrowed and in the lower forearm was only 3 mm. in diameter avascular atrophied and fibrotic. No obvious constriction or neuroma at any level. Ulnar nerve appeared normal (diam. 5 mm.) as far as epicondyle. Not exposed in upper half of forearm In lower half diameter much reduced (2 5 mm.) same consistency as median at this level. No response on stimulation."

This macroscopic finding of gross reduction in the diameter of the nerve without any obvious neuroma or constriction is now recognized to indicate nerve ischaemia.

(iv) *Muscles*

Evidence of muscle ischaemia is almost invariably present although the muscles affected vary from case to case. It is not always the most distal muscles which suffer most severely The consistence of the muscle bellies may provide sufficient evidence for a diagnosis of ischaemia they feel hard, wooden, or indurated Such muscles do not respond to electrical stimulation and are silent on electromyography If a biopsy is performed the muscles are greyish green or yellowish in appearance friable and avascular The histological picture is typical (p 203)

(v) *Contractures*

As the name Volkmann s ischaemic contracture implies, the presence of a contracture is the most striking feature of the condition. For example, in the



FIG 145 Macroscopic appearance of nerve from a case of Volkmann s contracture note gross reduction in calibre corresponding to point at which the nerve entered the area of ischaemia.

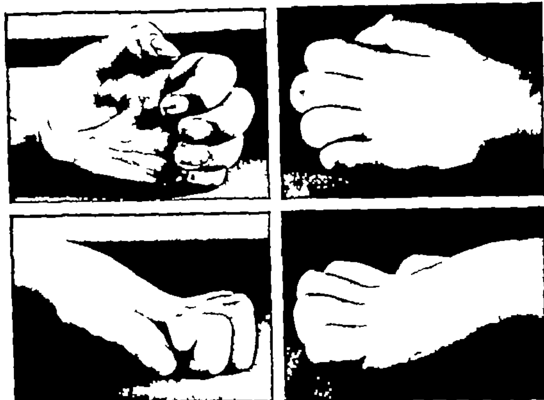


FIG 146. Showing typical appearance of hand in long-standing case of Volkmann's contracture.

upper limb the shortening of the long flexor muscles which usually bear the brunt of the ischaemia, produces not only a claw hand but also fixed flexion at the wrist. Because of the relative ischaemia of the hand, permanent joint changes occur more readily than in a straightforward nerve injury and as a result the contracture rapidly becomes permanent and exceedingly difficult to overcome by any orthopaedic procedure (Fig. 146) Similar changes take place in cases of ischaemic paralysis of the lower limb and produce a pes cavus with marked clawing of the toes and a shortened tendo Achillis

From the foregoing it will be apparent that the essential features of ischaemic paralysis whether associated with a closed fracture or due to a gunshot wound involving an artery are the same and it seems logical to suggest that they might be considered as one clinical entity with the designation ischaemic paralysis and that the use of the term Volkmann's ischaemic contracture (if it is used at all) should be restricted to describe cases of supracondylar fracture of the elbow complicated by ischaemic paralysis

C OTHER FORMS OF ISCHAEMIC PARALYSIS

Two other conditions in which ischaemia plays an important role in the development of the paralyses may be considered

(i) *Tourniquet Paralysis*

A transient paresis is a not uncommon sequel to the application of a tourniquet to a limb but, fortunately persistent paralysis is rare Eckhoff (1931) and Speigel and Lewin (1945) have reviewed the literature on the subject and in all only about 20 cases appear to have been reported In the present series there were two cases in which paralysis followed the use of a tourniquet

Case 36. A 23-year-old builder developed a tendon sheath infection in the right middle finger. This resulted in the development of a stiff finger for which, three months later, tenolysis was performed. During the operation, which lasted 50 minutes, a Martin's rubber bandage was applied round the arm as a tourniquet. When the patient recovered from the anaesthetic the entire right forearm and hand felt cold and numb, he was unable to move the fingers and could flex, but not extend, the wrist. During the following weeks slight improvement occurred. When seen at a Nerve Injuries Centre three months after the operation the findings were as follows: a right wrist drop was present; there was slight wasting of all the muscles of the right forearm and hand, but these did not feel ischaemic; active flexion of the wrist and fingers was present but very weak, the ulnar flexors being stronger than the median; the small muscles of the hand were all very weak; all muscles innervated by the radial nerve distal to triceps were paralysed; objectively all modalities of sensation were normal; the circulation and nutrition of the hand were excellent and there were good radial and ulnar pulses at the wrist. The electrical reactions showed that all muscles of the right forearm and hand responded briskly to faradism. Gradual improvement continued and when last seen nine months after the operation recovery was complete.

Case 37* L/Cpl. K. B., aged 38, had a right medial meniscotomy performed. A tourniquet (type not known) was applied during the operation which lasted 30 minutes. After operation there was some swelling of the knee and he complained of severe pain in the foot. At this time the bandages were not removed, but when this was done later there was evidence in the form of pressure sores that there had been considerable pressure in the popliteal fossa. Four months after this unfortunate sequence of events the state of the affected limb was as follows: the scars of the surgical incision, and of pressure sores over the knee, in the popliteal fossa and on the heel were sound. There were no contractures. The muscles of the anterior, lateral and posterior compartments of the leg and those of the sole of the foot were wasted, but of normal consistence. The long muscles were all active but weak (3–4) as was extensor digitorum brevis, but the small muscles of the sole were paralysed. The sensory findings are illustrated in Fig. 147. The right foot showed marked rubor and was warmer than the left, the skin was slightly atrophic and there was minimal digital atrophy. The dorsalis pedis and posterior tibial pulses were of good volume. Unfortunately it was not possible to follow this patient's progress.

The first of these cases is typical of those reported in the literature. Tourniquet paralysis is much more frequent in the upper than in the lower limb: of the previously recorded cases only two, that of Burman (1940) and Case 2 of Speigel and Lewin (1945) were in the lower limb. This has been attributed to the fact that the nerves of the thigh are better protected by muscles than those of the arm.

The nature of the nerve lesion in cases of tourniquet paralysis has been the subject of much controversy which centres around the question whether the damage is due to pressure or to ischaemia or to both. Allen (1938a) described what he called "necrosis of nerve fibres from direct pressure" in experiments with tourniquets on the limbs of rats and other animals. He (Allen, 1938b) showed that pure ischaemia produced by ligation of the abdominal aorta never produced persisting paralysis unless it was maintained long enough to cause gangrene, whereas a tourniquet applied to the thigh for two to three hours would produce a paralysis lasting at least four days. The most recent experimental work on this subject is that of Bentley and Schlapp (1943a, b) and Denny Brown and Brenner (1944c). These workers differ in that the former believe that a nerve block produced by pressure has different characteristics from one due to ischaemia, while the latter attribute the lesion entirely to ischaemia. Denny Brown and Brenner (1944c) describe three degrees of paralysis following the application of a tourniquet: paralysis with rapid, complete recovery on release of pressure, paralysis with delayed recovery without degeneration, and a lesion causing Wallerian degeneration. They found that the amount and duration of pressure necessary to produce any one of these lesions were extremely variable. The histological picture in the intermediate type of lesion consists of a segmental demyelination of the nerve fibres which is maximal at the site of pressure.

* This case has been reported elsewhere (Richards, 1946a) for another purpose.

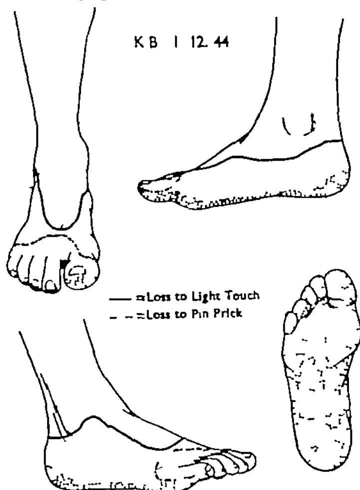


FIG 147 Case 37 Sensory findings. Stippling indicates area from which slow-pain response was obtained.

Clinically the majority of tourniquet paralyses correspond to this intermediate type of paralysis which was first described by Erb (1876) It consists of a purely motor paralysis which is not associated with any change in electrical reactions and which generally recovers in about seven to ten weeks. Crutch paralysis and Saturday night paralysis of the radial nerve are colloquial clinical diagnoses. The pathological lesion in all these conditions is probably similar to that observed by Denny Brown and Brenner (1944c) in their experiments but opportunities for confirming this do not arise

Permanent paralysis following the application of a tourniquet is rare. Details of some of the reported cases are inadequate, but Speigel and Lewin (1945) concluded that in only two could it be assumed that there might have been permanent paralysis. To these they added three cases of their own. In each of these only one nerve was affected the radial nerve in two cases and the external popliteal nerve in the other The nerves were explored at the level of the application of the tourniquet. The explorations were performed four to six months after the operations at which the tourniquet had been used In all three macroscopic lesions were found and stimulation of the nerves proximal to the lesions did not produce any response In these cases the fact that only one nerve was affected and that there was evidence of gross damage to the nerves at the site of application of the tourniquet are very strongly in favour of direct pressure upon the individual nerves being the cause of the paralysis rather than general

ischaemia of the limb It is unfortunate that nerve biopsies were not performed and that the appearances of the nerves more distal to the lesions were not ascertained for Seddon and Holmes (1945) have shown that ischaemia may affect only a single nerve

The second case reported above is rather different from the usual case of tourniquet paralysis in that sensory rather than motor manifestations were the presenting feature The clinical picture was that of a distal type of paralysis which resembled in permanent form the temporary centripetal paralysis produced by Lewis, Pickering and Rothschild (1931) by the application of a tourniquet to human limbs. They found that the application to the arm of a sphygmomanometer cuff inflated to a pressure above systolic blood pressure, for periods of up to 40 minutes produced a centripetal type of paralysis in which tactile and postural sensitivity suffered more readily than pain and thermal sensibility and motor functions were affected in a centripetal manner with extensor muscles suffering before flexor muscles They showed that this paralysis was due to ischaemia and differed from the paralysis produced by direct pressure on a short segment of a single nerve (ulnar) Sinclair (1948) has shown that the paralysis produced in this way is not strictly centripetal in its development. It is true that the most distal portions of the limb (the fingers) become anaesthetic first but he found that the median nerve was affected first, then the ulnar and later the medial and lateral cutaneous nerves of the forearm He suggested that this was due to the anatomical arrangement of the nerve trunks in the arm the median being the most easily compressed and also the largest of the nerve trunks so that it is perhaps more vulnerable to the effects of ischaemia. It is not yet clear why in this type of experiment some modalities of sensation are lost before others Lewis *et al* (1931) at first correlated this with the relative susceptibility of nerve fibres of different size to ischaemia, but later Lewis and Pochin (1938) showed that this hypothesis was not correct. Sinclair (1948) has suggested that the type of nerve ending involved as well as the type of nerve fibre, may be important in explaining the order in which the various modalities are lost. Pain which is subserved by the simplest type of receptor is the last sensation to be lost and during its disappearance there is a period in which pin prick results in a delayed exceedingly unpleasant type of response which provokes a marked affective reaction (Weddell Sinclair and Feindel, 1948) This was precisely the type of response which could be elicited from the sole of the foot in Case 37

A permanent distal paralysis of this type following the use of a tourniquet has not been recorded before and it is probable that the swelling of the limb in the post-operative period had as much to do with the onset of the paralysis as the use of the tourniquet. Parkes (1945) in his paper on traumatic ischaemia of peripheral nerves reported several cases in which gross swelling of a limb under tension appeared to be an important factor in the production of an ischaemic paralysis Of particular interest are the two cases in which nerve lesions were observed in patients suffering from haemophilia * In both instances a trivial injury to the elbow region resulted in gross swelling and bruising and, when this subsided, a distal type of paralysis affecting the small muscles of the hand and producing a glove type of sensory loss was present. Spontaneous improvement over a period of 18 months to two years was observed in both these cases.

It is somewhat tentatively suggested that a persistent distal paralysis of the type just described is the result of prolonged ischaemia of the whole limb distal

* Cases A and B of Parkes (1945 p 411)

to the site of pressure, whereas the more usual type of tourniquet paralysis is due to a small local area of pressure upon the nerve or nerves. The latter type of trauma may produce its effect either by direct pressure or by making a localized segment of nerve temporarily ischaemic.

(ii) *Anterior Tibial Syndrome*

This is an interesting condition affecting the muscles of the anterior tibial compartment of the leg which was apparently recognized for the first time during the recent war Cases have been reported both in the United Kingdom and in the U S A and the syndrome has been fully discussed by Hughes (1948) Carter Richards and Zachary (1949) and Bowden and Gutmann (1949) Six instances of this condition were encountered in the present series and they have been reported by Carter *et al* (1949 Cases 4–9) The following is a typical example

Case 38.* A 21 year-old seaman played a game of football one afternoon. During the game he did not sustain an injury to either leg. In bed that night he experienced an aching pain down the front of the left leg. This pain kept him awake and he reported sick next morning. Nothing abnormal was found at that time but the following day "signs of inflammation" were present over the front of the leg but he was afebrile. Two days later he was admitted to hospital as the signs over the front of the leg had increased. A radiograph of the leg revealed no abnormality and a tentative diagnosis of cellulitis was made. Ten days after the initial incident a foot drop was recorded and four days later it was discovered that the anterior tibial muscles did not respond to faradism.

Two months after the initial symptoms he was seen at a Nerve Injuries Centre. By that time all signs of inflammation had subsided but the muscles of the left anterior tibial compartment felt hard. There was a minimal drop-foot and a slight contracture of the dorsiflexors of the foot and extensors of the toes. The tibialis anterior extensor digitorum longus, extensor hallucis longus and extensor digitorum brevis were paralysed but the peronei and muscles of the posterior crural compartment were normal

There was no sensory disturbance, the nutrition of the foot was normal and good pulses were felt in both the dorsalis pedis and posterior tibial arteries.

The anterior tibial muscle group did not respond to any form of electrical stimulation. A biopsy of these muscles was performed. Macroscopically they were greyish, firm and avascular Microscopically the sections showed ischaemic fibrosis of muscle with fibrous tissue replacement

In most of the reported cases the condition has occurred in fit young men and the initial symptom of pain in the leg has developed either during or shortly after some activity involving strenuous use of the muscles of the lower limbs e g. playing football marching, long jumping. In two cases however the condition followed a transfusion into the veins of the leg and the writer knows of a third instance in which this occurred

The initial pain in the leg, which is often severe is followed by signs of inflammation over the anterior tibial muscles and then by inability to dorsiflex the foot and toes. When the signs of inflammation subside the anterior tibial muscles are found to be hard in consistence and the drop-foot is minimal owing to a contracture of the extensor tendons. Only the muscles of the anterior tibial compartment are affected the peronei and the flexor muscles escape In most of the cases signs of damage to the anterior tibial nerve are present paralysis of extensor digitorum brevis and/or a small area of sensory disturbance in the region of the first interdigital cleft The affected muscles do not respond to electrical stimulation and are silent on electromyography If a biopsy is performed the muscles are found to be necrotic and the microscopic appearances are indistinguishable from those seen in muscles obtained from cases of ischaemic paralysis due to gunshot wounds of blood vessels or from cases of Volkmann's ischaemic contracture.

* Case 9 of Carter *et al* (1949)

The aetiology of the condition is uncertain. It seems most likely that the condition is a sequel to trauma of the anterior tibial muscles resulting in swelling within the rigid anterior tibial compartment of the leg. This in turn interferes with the blood supply to the muscles so that they become ischaemic, and causes pressure upon the anterior tibial nerve The possibility that an element of arterial spasm also plays a part has not yet been fully excluded

Since the condition is apparently not met with in trained athletes, prophylaxis would appear to consist in properly graduated physical training before any strenuous exercise is undertaken. During the acute stage rest alone may be sufficient to prevent irreversible changes occurring, but as soon as the patient becomes unable to dorsiflex the foot and toes it seems reasonable to suggest that surgical decompression of the anterior tibial compartment should be performed as an emergency measure. When the condition is fully developed treatment becomes an orthopaedic problem In those cases which have been followed little or no recovery has occured even over a period of years.

3 *Traumatic Aneurysms and Peripheral Nerve Lesions*

Traumatic aneurysms and arteriovenous communications are not infrequently associated with injuries to the peripheral nerves On the other hand, an aneurysm is a relatively rare cause of a peripheral nerve lesion and was so described by most of those who wrote about nerve injuries after the First World War Makins (1919) stressed that either injured or intact nerves might be incorporated in the wall of an aneurysm and that, unless this was appreciated, important nerves might be needlessly damaged at operation. Fromme (1917) mentioned that nerve lesions were seldom encountered in association with aneurysms of vessels in the lower limb but that in the upper limb 13 of 16 aneurysms involving the subclavian, axillary and brachial arteries were associated with nerve lesions. He stated that the nerve lesions in these cases were due either to direct injury at the time of wounding, to expansion of the aneurysmal sac or to scarring around the aneurysm. Maurer (1939) found that 25 per cent of 71 aneurysms of the vessels of the upper limb were complicated by nerve lesions.

During the recent war Elkin and Woodhall (1944) reported four cases in which aneurysms in the upper limb were associated with nerve lesions, and four arteriovenous aneurysms in the lower limb two of which were accompanied by minimal signs of interference with nerve function Other cases in which aneurysms were the cause of nerve lesions have been described by Tönnis and Götze (1942) Wertheimer (1946) and Baker (1947) Most of these aneurysms were in the upper limb but in two an aneurysm of one of the gluteal arteries compressed the sciatic nerve.

In the present series there were 44 patients who had an aneurysm associated with a definite nerve lesion, which gives an incidence of only 0·01 per cent of aneurysms among peripheral nerve lesions A satisfactory figure for the incidence of peripheral nerve lesions in cases of aneurysm cannot be given since aneurysms uncomplicated by nerve lesions were not normally referred to a nerve injuries centre. One of the three centres from which the data were obtained was, however also a centre for peripheral vascular lesions and at that centre there was a total of 44 traumatic aneurysms and arteriovenous fistulae of the limb vessels, 17 of which were complicated by peripheral nerve lesions, an incidence of 38 6 per cent. The forty four cases of aneurysm occurred in a total of 243 cases with definite evidence of a combined neurovascular lesion

In 31 cases the lesion was in the upper limb and in 13 in the lower One patient A.31) had arteriovenous fistulae of both brachial and femoral vessels, but the atter was not associated with a nerve lesion All except one (A 6) were due to missile wounds The exception was a closed injury due to a fall off a motor cycle which caused an axillary aneurysm and a lesion of the brachial plexus.

i) *Aneurysm*

There were 27 arterial aneurysms and 17 arteriovenous fistulae. The distribution of these lesions is shown in Table 47

TABLE 47

Site of aneurysms

Vessel	Arterial	Arteriovenous	Total
Subclavian	2	0	2
Thoraco-acromial axis	1	0	1
Axillary	7	2	9
Brachial	10	8	18
Radial	0	1	1
Superficial femoral	2	2	4
Popliteal	1	2	3
Posterior tibial	3	1	4
Anterior tibial	1	1	2
Totals	27	17	44

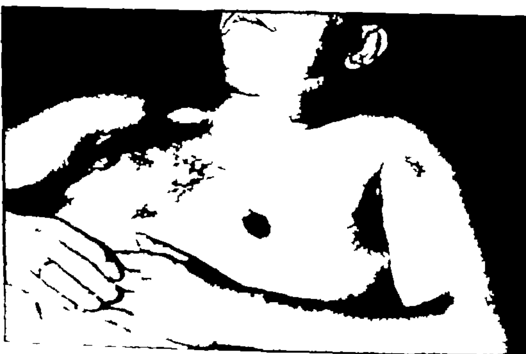


FIG 148. Case A 9 Appearances produced by large axillary aneurysm which compressed brachial plexus.

The aneurysms varied in size from a huge axillary haematoma (Case A 9 Fig. 148) to small aneurysms of the brachial artery (A.28) and posterior tibial artery (A 40) that were discovered only when the nerve lesion was explored. Similarly some of the arteriovenous fistulae had large sacs (A.12, 15 32) and others (A.24 and 42) were direct communications between artery and vein (aneurysmal varices) Details about the nature of the aneurysm were available in some cases and have been summarized in Table 48

TABLE 48

Type of aneurysm

Arterial	Haematoma	5
	False aneurysm	13
	Thrombosed sac	3
	No record	6
Arteriovenous	Aneurysmal varix	3
	With sac	4
	Not specified	10

In one case there were apparently two vascular lesions

Case A.43 An officer, aged 20 years, received multiple small wounds of the trunk and both lower limbs on September 3, 1944 A right lateral popliteal nerve lesion was noted within five days of wounding. One month later when a plaster cast was removed from the right leg, an aneurysm of the anterior tibial artery was recorded. When examined at a Nerve Injuries Centre six months after injury he was found to have a partial lateral popliteal nerve lesion, a partial posterior tibial nerve lesion and an arteriovenous aneurysm on the antero-lateral aspect of the leg centred 8 5 cm. below the head of the fibula. On May 2, 1945, the posterior tibial nerve was explored in the lower third of the leg, found partly divided (anterior division only) and resection and suture of the divided portion was performed. At the same time an arteriogram revealed that the popliteal artery had been damaged and that the aneurysm was apparently fed by dilated fibular collateral vessels. The aneurysm was not operated upon but was treated conservatively On July 15 there was a "firm swelling where the aneurysm had been the aneurysm has evidently thrombosed" Two months later however slight pulsation and a thrill were felt more distally over the line of the anterior tibial vessels and there was a faint engine-room bruit which has persisted unaltered to the date of the last examination on May 26, 1948. The note at this time states "There were two vascular lesions in this case, one in the upper and in the other in the lower third of the leg. The first cleared up spontaneously but the second has not done so. It seems likely that the lower fistula did not become apparent until after the upper one had closed "

The age of the aneurysms is of some importance. In the present series, operation was performed on all except three of the aneurysms. The age of the aneurysm was considered to be the time which elapsed between the date of injury and the date of operation. In the three cases that were not operated upon the diagnosis was made on the presence of a bruit which was heard by several observers over a period of days or weeks and which later disappeared If one case (A 40) in which the aneurysm was discovered accidentally at a nerve exploration three years after wounding be excluded, the extremes of duration were one week and 12 months with an average of 3 2 months. Twenty-nine of the 44 cases were operated on within three months from the date of injury and in only three cases including that just mentioned, was operation performed more than six months after wounding. It is therefore safe to conclude that any

neurological findings which might be directly related to the presence of a traumatic aneurysm must have developed within a comparatively short time

(ii) *Nerve Lesion*

(*a*) *Distribution* The distribution of the nerve lesions in relation to the site of the vascular injury is shown in Tables 49a and 49b for the upper and lower limb respectively

TABLE 49a

Distribution of nerve lesions related to site of vascular injury—Upper limb

Site of aneurysm	Nerves involved				
	Plexus	Median	Ulnar	Radial	Musculo-cutaneous
Subclavian	2	0	0	0	0
Thoraco-acromial axis	1	0	0	0	0
Axillary	3	4	4	4	2
Brachial	0	14	9	6	2
Radial	0	0	0	1*	0
Totals	6	18	13	11	4

* Posterior interosseous nerve only

TABLE 49b

Distribution of nerve lesions related to site of vascular injury—Lower limb

Site of aneurysm	Nerves involved				
	Sciatic	Lateral popliteal	Anterior tibial	Posterior tibial	Saphenous
Superficial femoral	2	1	0	0	2
Popliteal	1	1	1	0	1
Posterior tibial	0	1	0	4	0
Anterior tibial	0	1	1	1	0
Totals	3	4	2	5	3

In the 31 cases in which the injury affected the upper limb there were 52 individual nerve lesions (Table 49a) Excluding the six cases in which the brachial plexus was involved there were 12 in which more than one nerve was affected and 13 cases with a lesion of a single nerve The order of frequency with which the three major nerves were involved was median, ulnar and radial as might be expected from their anatomical course in relation to the major vessels. In the lower limb group the surprising finding was that the medial popliteal nerve was not involved alone in any case whereas there were four cases in which the lateral popliteal nerve was affected and the medial popliteal escaped damage.

(*b*) *Findings on clinical examination* When the clinical findings in the 44 cases were considered in terms of nerve function the data shown in Table 50a and b were obtained

TABLE 50a
Clinical findings—Upper limb

Nerve	Loss of function	
	Complete	Incomplete
Brachial plexus	0	6*
Median	9	9
Ulnar	4	9
Radial	7	3
Musculo-cutaneous	3	1
Posterior interosseous	1	0
Totals	24	28

* See Table 51

TABLE 50b
Clinical findings—Lower limb

Nerve	Loss of function	
	Complete	Incomplete
Sciatic	0	3
Lateral popliteal	2	2
Anterior tibial	1	1
Posterior tibial	1	4
Saphenous	1	2
Totals	5	12

TABLE 51
Clinical findings—Brachial plexus lesions

Case no	Aneurysm	Nerve lesion
A.1	Subclavian	Slight lesion of complete plexus, chiefly median
A.2	Subclavian	Slight lesion, chiefly of upper plexus
A.3	Thoraco-acromial axis (Fig. 149)	Complete lesion of lateral and posterior cords
A.5	Axillary	Complete lesion of lower trunk
A.6.	Axillary	Complete plexus lesion except pectoral nerves
A.9	Axillary	Incomplete lesion of lateral and posterior cords

The six lesions of the brachial plexus have been included in the group of incomplete lesions since in none of them was there a complete interruption of the whole plexus. In some of the cases, however the clinical findings suggested

: part of the plexus had been completely divided and these cases have there- : been considered separately in Table 51

refore, of the 69 individual nerves that were affected in the upper and the er limb the clinical evidence pointed to complete interruption in 32 instances , an incomplete lesion in 37 In so far as the nerve lesions themselves were cerned the clinical syndromes did not differ significantly from those observed similar cases in which the nerve lesions were not complicated by vascular ines.

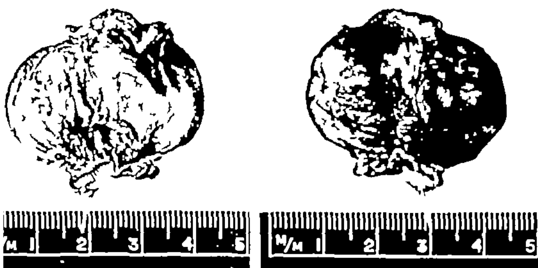


FIG 149 Case A3 Aneurysm of thoraco-acromial axis note grooves in sac produced by lateral and posterior cords of brachial plexus.

(c) *Findings at operation* Details of the state of the nerves at the time of the eration upon the aneurysm or at a subsequent nerve exploration were ailable in 22 of the 31 upper limb cases and six of the 13 lower limb cases. e findings in the former group are recorded in Table 52. In the lower limb one ploration of the sciatic nerve and two of the lateral popliteal nerve revealed parently normal nerves Three of the five posterior tibial nerve lesions were plored in one case the nerve was completely divided and in the other two rtually divided

TABLE 52

Operative findings—Upper limb

Nerve	Normal	Division		Adherent to sac
		Complete	Partial	
Brachial plexus	–	1*	–	1
Median	3	3	1	8
Ulnar	5	1	1	1
Radial	2	1	1	–
Musculo-cutaneous	1	1	–	–
Totals	11	7	3	10

* Division of lower trunk

Thus in the upper limb in 10 of 31 cases of aneurysm associated with peripheral nerve lesions one at least of the injured nerves was intimately connected with the aneurysm. It is also evident that the median nerve is more frequently involved in the wall of an aneurysm than any of the other major nerves of the upper limb a finding which is consistent with the anatomical relations of the median nerve with the axillary and brachial vessels (Fig 150) In the lower limb on the other hand there was no indication from the findings at operation that any of the nerve lesions could be attributed to the nerve being closely adherent to an aneurysmal sac.

(*d*) *Development of nerve lesion* In all except three of the upper limb cases the history indicated that the nerve lesions had been present since wounding and had either improved or remained stationary thereafter

In one case (A.4) severe pain developed about one month after the date of injury and paralysis appeared to increase. In another (A.15) a brachial aneurysm was operated upon six weeks after injury this operation was followed by severe haemorrhage and a second operation had to be performed. An incomplete median and ulnar palsy had been present before these operations, but subsequently there was greater loss of function in these two nerves and a radial palsy also developed. In a third case (A.5), following the operation on the aneurysm, there was increased loss of function in the median nerve but this recovered slowly in the three months after operation. In the lower limb group the histories of three cases (A.32, 34 and 36) provide unequivocal evidence that the nerve lesions developed subsequent to the operations for the aneurysms.



FIG 150 Case A 19 Aneurysm of brachial artery note 'waist' caused by median nerve where it crossed aneurysm and was densely adherent to sac.

(*e*) *Responsible factors* From a consideration of the clinical picture the findings at operation and the history of the development of the nerve lesions, an attempt has been made to assess the factors responsible for the nerve lesion in each case. The possible factors were considered to be direct trauma pressure from the aneurysm and ischaemia It is of course possible for all three factors to be present in any one case and even to affect one nerve. The conclusions which follow must be regarded only as probabilities deduced from the evidence available in each case.

(1) Direct trauma to nerves at the time of injury This does not require further elaboration In many cases adjacent nerves were damaged by the trauma which caused the vascular injury In 15 of the 44 cases this was the most likely cause of the nerve lesion 14 of these were due to gunshot wounds, the fifteenth was a traction lesion of the brachial plexus.

(2) Pressure upon nerves by the aneurysm This group includes those cases in which the nerve or nerves was found to be undamaged but in close relationship to the sac of the aneurysm, or in which a rapid improvement in nerve function followed surgical treatment of the aneurysm Thirteen cases are included in this group There were two cases of subclavian aneurysm and two of axillary aneurysm with pressure on the brachial plexus Seven of the ten

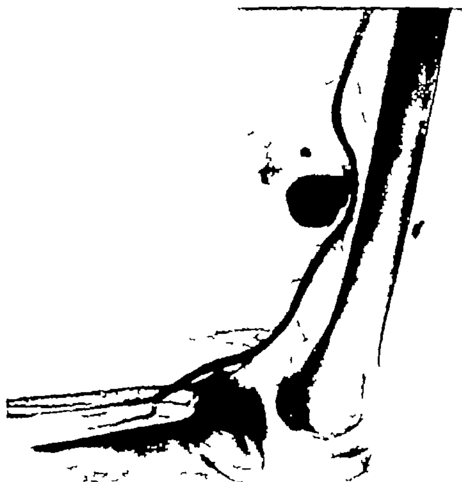


FIG. 151 Case A.33 Arteriogram showing large aneurysm of femoral artery which compressed lateral popliteal nerve note that aneurysm is much larger than cavity which is filled with contrast medium.

cases in which the nerves were adherent to the aneurysmal sac (see Tal are in this group the other three have been included in the previous gr the nerves, although adherent to the sac, were definitely damaged Two popliteal nerve lesions were considered to be due to pressure from femoral aneurysm in one case (Fig. 151) and a popliteal aneurysm in the Whether the effects of the aneurysm extended beyond those of pres uncertain Lyons and Woodhall (1949) have reported two cases in whic attributed division of nerve fibres to erosion by a pulsating aneurysm. case (A 22) in the present series the aneurysm appeared to be within the sh the median nerve, the fibres of which were splayed out over the surface of t

(3) Ischaemia either as a result of the arterial injury or developing subs to the surgical treatment of the aneurysm This was thought to be the ca the nerve lesion in five cases Four of these have been considered in the pre section of this report (see pps 191 193 Table 35) The other was no sidered there because only the saphenous nerve was affected.

(4) In four cases it was considered probable that more than one of the factors was present to account for the nerve lesions

(i) Case A.4 An axillary aneurysm. One month after injury onset of severe pain whic for ten days until the aneurysm was operated upon. All the major nerves of the upp were affected and paralysis increased at the time the pain developed. At operation the nerve was found completely divided and was grafted from the musculo-cutaneous whi also divided. The radial and ulnar nerves were intact. In this case direct trauma and aneu pressure were certainly factors and ischaemia may also have contributed.

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(iii) Case A 15 A brachial aneurysm was operated upon six months after injury this tion was followed by severe haemorrhage and a second intervention was necessar incomplete median and ulnar palsy had been present before these operations, but subseq there was greater loss of function in both of these nerves and a radial palsy also deve The nerves were later explored and "no solution of continuity" was recorded. It seems pro that after the operations, ischaemia aggravated a lesion already present and due to pressure from the aneurysm or trauma at the time of wounding.

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In the remaining seven cases the available data were insufficient for conclusion regarding the factors responsible for the nerve lesion to be reac

(iii) *Nutrition of Limb*

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latter has already been discussed (p 192) The former was a case in which an aneurysm of the axillary artery had been incised in the mistaken belief that it was an abscess. To control the haemorrhage which followed the subclavian artery was ligated and the hole in the axillary artery closed The median and ulnar nerves were known to be divided with a 5·0 cm gap and there was severe pain Stiff joints and pronounced nutritional changes in the digits were noted in five other cases in which the lesion was in the upper limb In four cases in the lower limb group ischaemia was considered as a probable cause of the nerve lesions, but in none of these was the nutrition of the skin and muscles seriously affected In the remaining 33 cases the nutrition of the limbs was as good as that of limbs with similar nerve injuries uncomplicated by any vascular lesion

(iv) *Pain*

There was an impression among those working in the Nerve Injuries Centres that pain was a prominent feature in cases complicated by aneurysms Makins (1919) states Pain from pressure on neighbouring nerves is not an uncommon symptom, but it is rarely persistent and diminishes *pari passu* with the localization and contraction of the haematoma or aneurysm Pain coming on during the course of the case is usually a sign of extension of the aneurysm. Tönnis and Götze (1942) described four cases of peripheral nerve lesions associated with aneurysms in which pain was severe and was at once relieved by operations upon the aneurysms.

Pain or paraesthesiae were recorded as symptoms in only 17 of the 44 cases. From the various descriptions in the case notes the pain was classified as severe moderate or slight, with the following results

TABLE 53

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In five of the cases with severe pain the pain was present from the time of wounding until the operation upon the aneurysm, when it was dramatically and

completely relieved One of these cases (A 1) was remarkable in that the patient had an undetected aneurysm of the subclavian artery for six months before a particularly severe exacerbation of his pain led to its discovery The sixth case with severe pain was a good example of Makins dictum that pain arising during the course of the case indicates extension of the aneurysm As already mentioned (p 230) severe pain developed about one month after wounding and was associated with increased paralysis The pain persisted for ten days until operation was performed and in this case also the result of the operation upon the pain was dramatic.

In the cases with moderate or slight pain the tendency was for it to disappear gradually in only one case is there a definite record of pain continuing after the operation on the aneurysm.

From the foregoing the following conclusions may be drawn

(1) When a nerve lesion is complicated by an aneurysm pain is not always present.

(2) However severe pain sometimes occurs, and will be relieved immediately by dealing with the aneurysm

(3) If a patient with a wounded limb complains of severe pain which is not related to the anatomical territory of one or more nerves an aneurysm should be suspected

(*a*) *Treatment of aneurysm* As already mentioned (p 224) surgical exploration of the aneurysm was performed in all except three of the 44 cases. Details of the operative procedures employed are recorded in Tables 54a and 54b It will be noted that spontaneous cure occurred in four cases, two arterial aneurysms and two arteriovenous aneurysms but in one of the latter the lesion was later explored and a thrombosed venous sac removed. In two of the arterial cases in which the operation upon the aneurysm had been performed before the patient came to a Nerve Injuries Centre, the exact details of the procedure were not recorded.

The procedures were those usually adopted for the treatment of aneurysm the classical operations of excision of an aneurysm with proximal and distal ligation of the artery and quadruple ligation with excision of an arteriovenous fistula, were most commonly employed. As far as could be ascertained from the notes, in none of the cases was the surgeon influenced in his choice of procedure by the presence of the nerve lesion

In five cases the nerve lesion was apparently worse after operation (see p. 228). One of these cases was one of the two in which the exact details of the operative treatment were not recorded, but it was known that a second operation upon the aneurysm was necessary because of haemorrhage (Case A 15) In a second case (A 5 see p 230) the increased paralysis after operation was slight and recovery took place within three months. In the other three cases the lesion was in the lower limb and in each the femoral artery was implicated the excision of an aneurysm the excision of an arteriovenous fistula and proximal ligation of the artery in Hunter's canal for a popliteal aneurysm were the operations responsible It would appear that in these three cases the site of the lesion and not the procedure employed was responsible for the adverse results of the operations.

(*b*) *Treatment of nerve lesion* Details of the treatment of the individual nerve lesions are presented in Tables 55a and 55b In the 69 individual nerve lesions

TABLE 54a

Treatment—Arterial aneurysms

Procedure	No of cases
Excision of aneurysm with ligature of artery above and below	12
Evacuation of haematoma and ligature of artery	2
Removal of aneurysm intact	1
Obliterative endoaneurysmorrhaphy	1
Proximal and distal ligature without removal	3
Proximal ligature only*	4
Spontaneous thrombosis of sac	2
Details of operation not recorded	2
Total	27

Two cases of subclavian ligature for axillary aneurysms, one after incision of the aneurysm, and in this case the hole in the axillary artery was also repaired one case of ligature of the femoral artery in Hunter's canal for a popliteal aneurysm, and one case in which both posterior tibial and peroneal arteries were ligated for an aneurysm of the posterior tibial artery

TABLE 54b

Treatment—Arteriovenous aneurysms

Procedure	No of cases
Quadruple ligation and excision	9
Quadruple ligation without excision	2
Proximal ligature of artery and vein	1
Ligation of arteriovenous communication	1
Proximal and distal ligature of artery with obliteration of vein	1
Removal of vein and sac with closure of hole in artery	1
Spontaneous cure	2
Total	17

* In one of these cases the thrombosed venous sac was later removed

TABLE 55a

Treatment of nerve lesions—Upper limb

	Brachial plexus	Median	Ulnar	Radial	Musculo-cutaneous	Total
Suture	1	4	2	2	–	9
Graft	–	1	–	–	–	1
Neurolysis	–	7	1	–	–	8
Conservative	4	5	9	8	3	29
Irreparable	1	1	1	1	1	5
Totals	6	18	13	11	4	52

Posterior interosseous nerve—tendon transplant

TABLE 55b

Treatment of nerve lesions—Lower limb

	Sciatic	Lateral popliteal	Anterior tibial	Posterior tibial	Saphenous	Total
Suture		–	–	2*	2*	2
Neurolysis	–	2	–	1	–	3
Conservative	3	2	2	2	3	12
Totals	3	4	2	5	3	17

* One partial suture

here were only 11 sutures and one nerve-graft. In preparing the data for these wo tables exploration of a nerve has not been considered as a neurolysis only hose cases in which there was a record of the nerve being freed from scar issue or the wall of an aneurysm have been considered under the heading neurolysis If the 11 cases in the latter group are added to the sutures and he graft, there were 23 cases in which active surgical treatment may have nfluenced the result. The length of nerve which had to be resected in the welve cases in which surgical repair was performed is shown in Table 56. It will be noted that on the whole the length of nerve resected was small.The two exceptions were the case in which a nerve graft was required and a case in which a lesion of the median nerve in the forearm was associated with an aneurysm in he arm.

TABLE 56

Length of nerve resected

Case no	Nerve	Length of resection (cm.)
A.3	Posterior cord	1
A.4	Median	7*
A.11	Ulnar	2
A.16	Median	4
A.17	Radial	2 5
A.18	Median	3
A.22	Median	3
A.25	Ulnar	3
A.26	Median	6·5
A.27	Median	1
A.28	Radial	3
A.39	Posterior tibial	2
	Average resection	3 2

* Nerve graft

In most of the cases the nerve lesion was exposed and dealt with at the operation upon the aneurysm. In thirteen cases, however an operation that was regarded as a nerve exploration only was performed In three cases an

aneurysm was not suspected until it was exposed at a nerve exploration the vessels involved in these three cases were the thoraco-acromial axis the brachial artery and the posterior tibial artery In three cases the nerve lesion was explored because the operation upon the aneurysm had been performed elsewhere and there was insufficient information about the state of the nerves In four cases the nerve lesion was explored separately because it would have been difficult to expose the aneurysm and the nerve lesion through the same incision As might be expected these four cases were all in the lower limb

A.33 A femoral aneurysm with a sciatic nerve lesion.

A.34 A femoral aneurysm with a lateral popliteal nerve lesion.

A.41 A posterior tibial aneurysm with a lateral popliteal nerve lesion.

A.43 An anterior tibial arteriovenous aneurysm with a posterior tibial nerve lesion

In two cases the nerves were explored after spontaneous thrombosis of the aneurysm had occurred In the remaining case in this group there was a double lesion of the median nerve and the nerve exploration was for the second lesion in the forearm

The interval between the date of injury and the operation is of some interest in these cases. There was only one case in the series which was not operated upon (A.39) The interval between injury and the first operation in the remaining 43 cases is recorded in Table 57

TABLE 57

Interval between wounding and operation

Time in months	0–3	3–6	6–9	9–12	over 12
No of cases	21	13	7	1	1

These figures indicate that the patient who had an aneurysm with a nerve lesion was operated upon relatively early There are many reasons why this should be. Undoubtedly the most important was that the presence of an aneurysm was regarded as an absolute indication for operation and therefore a nerve lesion which might otherwise have been treated conservatively for a time was explored as soon as the limb was in a suitable condition Since the aneurysms were practically all the result of wounding by small missiles, healing took place rapidly and conditions were ideal for an early exploration In many cases too the presence of an aneurysm or arteriovenous fistula attracted attention to a nerve lesion which might otherwise have been missed This was by no means always the case, however for as already pointed out in three cases a nerve lesion was diagnosed but the presence of the aneurysm was unsuspected until operation An aneurysm that was increasing in size causing pain or in danger of becoming infected might have been the reason for early operation, but these factors hastened operation in only two cases (A 9 A.34) and may have influenced the decision in another (A 4)

(v) *Prognosis*

The end-results of the 44 cases in this group were on the whole most satisfactory As already mentioned there was one amputation (A 10) and one patient (A 14) had a comparatively useless arm because of a severe degree of ischaemia In five cases the nerve lesion was a comparatively minor one and after the

aneurysm had been dealt with, the patient was left with little disability (Cases A 1 2, 35 38 and 44) One patient had a tendon transplantation performed for a posterior interosseous palsy with an excellent result. In eight cases, for a variety of reasons the follow up period was less than 12 months and these have been excluded from Table 58 which shows the results in the remaining 28 cases.

The results compare favourably with those of similar cases uncomplicated by aneurysms nerves with lesions in continuity recovered well and nerves which were sutured did as well as could be expected considering that most of the lesions were situated proximally Most of the patients had a reasonably useful limb If the results in this group of cases be compared with those presented on page 211 for the cases of ischaemic paralysis (and the two are comparable in many respects) it will be apparent that the prognosis in a case of aneurysm with associated peripheral nerve lesions is better than that in many cases of combined neurovascular injury

TABLE 58

Progress

Case no.	Nerves involved	Type of lesion	Follow-up (months)	Recovery		
				Motor	Sensory	Function
A.3	Brachial plexus (posterior and lateral cords)	Suture	60	Good	Fair	Good
A 4	Median Radial Ulnar	Graft In continuity	55	Fair	Fair	Fair
A.5	Brachial plexus	Uncertain	24	Fair	Fair	Poor
A.6	Brachial plexus	Traction (?)	38	Good	Fair	Good
A 7	Radial	In continuity	60	Excellent	Good	Excellent
A.11	Median Ulnar Radial	In continuity	46	Fair	Good	Good
A.12	Ulnar	Suture	21	M1	S0	Good
A 13	Median Ulnar Radial	In continuity	37	Good	Fair	Fair
A.15	Median Ulnar Radial	In continuity	15	Good	Good	Good
A 16	Ulnar	In continuity	35	Nil	Nil	Good
A 17	Median	Suture	46	M1	S2	Fair

TABLE 58 (*continued*)

Case no	Nerves involved	Type of lesion	Follow-up (months)	Recovery		
				Motor	Sensory	Function
A 19	Median	Suture	59	M3	S2	Excellent
A.20	Median } Radial }	In continuity	42	Good	Good	Good
A.21	Median } Ulnar }	In continuity	33	Good	Good	Good
A.23	Median Ulnar	Suture In continuity	60	Fair	Good	Good
A.25	Median } Ulnar }	In continuity	60	Good	Good	Good
A.26	Median Ulnar	In continuity Suture	24	Good	Good	Fair
A.27	Median	Suture	46	M3	S2	Good
A.29	Radial	Suture	60	M4	S4	Excellent
A.31	Median	In continuity	56	Good	Fair	Good
A.32	Sciatic	In continuity	31	Good	Fair	Fair
A.33	Lateral popliteal	In continuity	48	Poor	Fair	Good
A.34	Sciatic	Ischaemic	48	Good	Fair	Good
A.36	Sciatic	Ischaemic	29	Good	Good	Good
A.37	Lateral popliteal	In continuity	14	Good	Fair	Good
A.40	Posterior tibial	Suture	42	M2	S1	Fair
A 41	Lateral popliteal } Posterior tibial }	In continuity	48	Good	Good	Excellent
A.43	Lateral popliteal Posterior tibial	In continuity Partial suture	57	Good	Fair	Good

Note Cases in which a single nerve was sutured have been assessed according to the standard M.R.C. method (p. 4). For all other cases the method of assessment described on pps. 211–212 has been adopted. The follow-up period has been reckoned from the date of wounding except in cases where a single nerve was sutured; in those it has been reckoned from the date of suture.

(vi) *Conclusions*

From a survey of 44 cases in which a traumatic aneurysm or arteriovenous communication in a limb was associated with a nerve lesion in the same limb, the following conclusions have been drawn

(1) Aneurysms and arteriovenous fistulae are infrequent complications of peripheral nerve lesions but probably more than 25 per cent of traumatic aneurysms or arteriovenous fistulae of limb vessels are associated with nerve lesions.

(2) In the upper limb multiple nerve lesions are as frequent as lesions of a single nerve and the median is the nerve most frequently affected In the lower limb lesions of the sciatic nerve or its branches may occur depending on the site of the aneurysm

(3) Pressure upon nerves by the aneurysm or involvement of the nerves in the wall of an aneurysmal sac accounts for only about one third of the nerve lesions. The remainder are due to direct trauma at the time of wounding to ischaemia, or to a combination of these two factors.

(4) In most cases in which an aneurysm or arteriovenous fistula and nerve lesion co-exist the nutrition of limbs is as good as in cases with similar nerve lesions uncomplicated by vascular injury Gangrene is rare and amputation seldom necessary

(5) Pain is not always a symptom in such cases but is more common than in uncomplicated nerve lesions and may occasionally be severe. If so operation upon the aneurysm brings dramatic relief

(6) Early operation is the rule in cases of aneurysm associated with nerve lesions This is largely because the presence of the aneurysm or arteriovenous communication is regarded as an absolute indication for operation and because the majority of such cases are due to small wounds which heal rapidly

(7) The aneurysm and the nerve lesion can usually be dealt with at the same operation

(8) Rarely if ever does the presence of the nerve lesion influence the choice of procedure for dealing with the aneurysm, and the classical procedures of proximal and distal ligation with removal of an aneurysm and quadruple ligation and excision of an arteriovenous fistula are preferred.

(9) In about one third of the cases active surgical treatment of the nerve lesion is required This may take the form of resection and suture, freeing of the nerve from scar tissue or from the wall of an aneurysm rarely nerve grafting

(10) The prognosis in cases of nerve lesions complicated by aneurysms both as regards neurological recovery and the ultimate function of the limb is as good as that in cases with similar but uncomplicated nerve lesions.

VI

PART I ELECTRICAL DIAGNOSIS OF PERIPHERAL NERVE INJURY

by A E. RITCHIE

1 Introduction

.ECTRICAL methods used in the diagnosis of nerve injury are of three kinds ch based on different physiological principles. They are (1) the use of electric ocks deliberately produced and applied so as to bring about excitation of rve or contraction of muscles, (2) the detection of the minute and transient ctrical changes arising in active nerve and muscle tissue and (3) the use of ctrical techniques to measure changes indirectly concerned with nervous nction, such as skin resistance and skin temperature This section is con rned only with the first

Electrical stimulation has been used diagnostically since the end of the neteenth century Its value as a clinical adjunct depends on a thorough under nding of the underlying physiological principles, and upon a high standard technique. Successful electro-diagnosis calls for a systematic routine and ould be undertaken by an operator able and willing to treat the procedures scientific aids to clinical examination Although the basic principles are simple, any variations in their application have been used and the following section escribes those that have been found valuable in the study of nerve injury

2. Principles and Methods in Artificial Stimulation of Nerve and Muscle

wo properties of excitable tissue are examined in electro-diagnosis by imulation The first is the normal polarization of healthy nerve and muscle ell boundaries, which can be altered by application of an external electromotive orce. The second is the adaptive or accommodative property of the cell embrane, whereby a constant stimulus tends to become ineffective with the assage of time. *Although these phenomena polarization and accommodation,* re both reflections of the nature of the cell and are related they are usually ssessed separately

A. SUDDEN SHOCK DEPOLARIZATION

The simplest observation in artificial stimulation is that the sudden applica ion of electric current to nerve or muscle triggers off the natural activity of ach The amount of the shock together with its duration forms a measure of he excitability of the tissue under examination. As diagnosis depends on a lifference in excitability between nerve fibre and muscle cell, knowledge of the haracteristics of the shock required to provoke a response is most important f either nerve or muscle be stimulated under controlled conditions with shocks hich vary both in intensity and duration the fundamental relationship known is the *intensity-duration curve* can be observed and all sudden-shock liagnostic methods are based on some aspect of this relationship

Fig. 152 represents the general law relating intensity to duration of stimulus for threshold or constant response The *primary observation is that the briefer*

a stimulus is, the more intense must it be to be effective this holds good over a wide range in which excitation can occur and the limits of the range are of some practical importance. At one extreme when the shocks, however strong, are so short that they cannot bring about depolarization at all, the effect is utilized in the passage of very rapidly alternating *diathermy* current for heating tissues without motor or sensory stimulation. The other limit is where the applied stimulus is so weak that it fails to depolarize, however long it be applied. An important threshold in stimulation the rheobase, is defined as that intensity of current or voltage (depending on technique) which is just sufficient to cause excitation if allowed to persist indefinitely In practice, the duration for human skeletal muscle need not exceed one second and the intensity required represents the minimum for any type of effective shock.

If the duration of the shock be progressively reduced and the intensity needed for excitation is recorded at each reduction a curve of the type shown in Fig. 152 results this is an expression of the excitability characteristic of the tissue being studied

All methods employing sudden shock techniques are based on the intensity duration curve, and some involve the recording of the complete curve. Details of practical importance in procedure, and errors arising from failure to appreciate them, will be discussed in Section 4 (iv) Standard texts on electrotherapy and diagnosis should be consulted for an outline of the methods, and for sites of application of electrodes. Certain procedures which have been extensively used for diagnosis by sudden-shock methods are now described

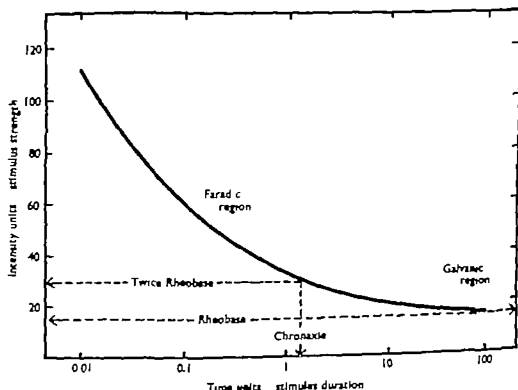


FIG 152. The relationship between the duration of a stimulus and its intensity for constant response. The rheobase is that intensity required of an indefinitely prolonged stimulus, and corresponds to the galvanic threshold. Chronaxie is the minimum effective duration of a shock of twice rheobasic strength.

(i) *Galvanic faradic Test*

For over sixty years this test has been used to differentiate between normal innervated muscle and denervated muscle. It is the best known and most widely used electro-diagnostic method and depends on the use of shocks of widely different durations. Normal muscle can readily be made to contract by the application of the output from the secondary winding of the induction or faradic coil the stimuli are usually repeated at a tetanizing rate by action of the primary circuit interruptor Denervated muscle, by contrast, will not respond to faradic current of tolerable intensity but is nevertheless electrically excitable the output from a battery or other source of direct (galvanic) current causes contraction on the make and if strong enough on the break also This distinction between faradic and galvanic responses arises because of the relative durations of the two types of shock and is a crude expression of the intensity-curve of Fig. 152.

The output from an induction coil while extremely inconstant and not measurable, is characteristically of short duration Galvanic current, on the other hand being controlled by a hand key or other slow acting contact maker persists for a relatively long time and is accordingly effective at a low intensity It is not practicable to specify intensity and duration in either case and the test is a qualitative one only Normal muscle, responsive to the brief faradic shocks is in fact excited through its nervous content and is of course, responsive to the galvanic shock also Denervated muscle is excited directly and requires a longer lasting stimulus. Muscle tissue in this respect is very much less excitable than is nerve.

Normal and denervated muscle differ not only in their excitabilities but also in their responses The reaction of denervated muscle to a galvanic shock is sluggish both in contraction and relaxation and tends to be localized under the stimulating electrode, in contrast with the brisk generalized twitch produced by a single shock to normal muscle, or the quickly developed and relaxed tetanic response to faradism. Recognition of this difference is an important feature of electro-diagnosis The use of the so-called polar formula at one time considered an adjunct to testing with galvanism, has been found to be erratic and misleading and has no place in modern diagnostic work.

(ii) *Condenser Discharge Testing*

Electro-diagnosis by means of condenser discharges was described by Lewis Jones (1913) and extensively used by Worster Drought (1920) This method represents an attempt at a single quantitative expression of excitability A constant potential (100 volts) is used to charge capacitors of varying sizes these are subsequently discharged in turn through the electrodes and muscles concerned and the size of capacitor needed to produce a twitch is taken as a measure of excitability The variable factor is therefore the duration of the shock the intensity being fixed Shock duration varies according to the capacity used provided that the tissue resistance remains constant during the period of test. This requisite is usually satisfied but the results are not directly comparable from one subject or muscle to another unless special precautions are taken The method is mechanically and electrically simple and can give good results but for quantitative measurement it has now been superseded by techniques in which both intensity and duration are varied

(iii) *Chronaxie Determination*

With the introduction into physiology of the concept of chronaxie as an index of excitability various methods have been developed for its measurement in man The classic monograph of Bourguignon (1923) gives a full account of the principles and practice of human chronaxie determination It will be appreciated (Fig. 152) that chronaxie is by definition specified in units of time, and is that time for which a stimulus of twice rheobasic strength must last in order to be effective. Chronaxie measurement therefore involves a preliminary rheobase determination, and represents an arbitrary point on the intensity duration curve. Determination of chronaxie as a single index is now rarely used, since it can always be deduced from an intensity-duration record, which gives additional information and is little more difficult to measure. Moreover single chronaxie figures in man are of very little value unless the exact technique of their determination is specified a point that has only recently been appreciated (Walter and Ritchie 1945)

(iv) *Intensity-duration Curves*

The obviously desirable achievement of recording the complete curve in routine nerve injury testing has had to wait upon the development of appropriate electrical equipment for the technical problem is not an easy one. Early attempts, using condenser discharges or the mechanical Keith Lucas contact breaker have been recorded by Adrian (1917) with very good results.

The appearance of modern electronic apparatus specially devised for the purpose of ID curve recording in man may be dated in this country from the publication of a number of papers during the War years (Bauwens, 1941a, b Ritchie, 1944 Walter and Ritchie, 1945) There are a number of important technical considerations. The use of exponentially shaped condenser discharges to obtain different durations has been shown to be less efficient for diagnosis than square shocks i e. pulses of electricity where rise and fall are very short compared with their persistence. It is not easy to produce such square pulses over the wide range of durations called for and some of the early instruments were undoubtedly inaccurate. The measurement of the other variable, intensity has given rise to a good deal of confusion, as it may be done in either of two ways, for strength or intensity of shock can be measured either as current (milliamperes) or as potential (volts) The point to remember is that as the electrical conditions prevailing at the surface of the nerve or muscle cell are never exactly known (and it is these conditions which are the exact measures of excitability), the applied shock must be measured in terms of voltage at the skin electrodes, or current through these electrodes. It is necessary to assume that conditions in the tissues between the electrodes do not change during the process of examination This assumption is only partly true, and the changes that occur depend on the type of input applied through the electrodes.

However modern technique has developed methods of compensating for such changes during examination and for variation from one patient to another This technical advance has however introduced one important complication for machines which deliver and measure their square waves as known current differ in design from those which deliver an input in terms of known voltage. Owing to the fact that the tissues of the body do not act as simple resistances, but possess considerable electrical capacity as well the voltage and current waves do not precisely correspond, and the actual figures for ID curves differ

according to the technique used It is therefore essential to specify the technique employed when displaying such a curve The question of the influence of technique on such curves has been reviewed by Ritchie (1948) and requires further investigation It must be appreciated that techniques that specify current or voltage are both perfectly valid Each method has advantages but the results cannot be directly compared one with another The chronaxie figures obtained from the same muscle under the same conditions, with the generator as the only variable, may differ by a factor of ten or more. There is therefore a need for some terminology defining the type of generator used in taking any particular record It is accordingly suggested that the distinction might well be made as follows. The relationship between the strength of a stimulus and its persistence will be referred to as the Intensity Duration curve, abbreviated to ID Actual recorded curves and chronaxie figures deduced therefrom will be referred to as Voltage-Time curves (VT) if taken with a low impedance generator whose output is measured in terms of volts across the electrodes or as Current Time curves (CT) if a high impedance stimulator with output specified in current (milliamperes) is used. A complete account of any stimulator would of course be given by a statement of its effective output impedance e g. ID curve 400 000 ohm stimulator which would refer to a particular current-stabilized instrument. In practice, the relationship between recorded curves and the generator impedance has not yet been fully worked out.

A number of experienced workers are of the opinion that the VT type of stimulation is better tolerated by patients, and therefore valuable in difficult cases or in children This is a practical consideration for any electrical stimulation involves a certain amount of discomfort and the VT type may enable a curve to be recorded when the patient is intolerant of the CT shocks Those who favour the CT instrument claim that its relative independence of variables such as skin resistance enables testing to be done more rapidly and with greater accuracy It is probable that both types have particular spheres of usefulness and as far as is known the diagnostic results are comparable though the figures recorded differ

In the taking of ID curves, very careful attention to technique is essential to obtain statistically reliable results and the process is time-consuming the threshold intensities for several different pulse duration values have to be recorded and subsequently plotted The preparation of the skin and electrodes, and the exact location of the motor point are important. The technique cannot satisfactorily be done as a routine task by an operator who is uninformed or uninterested There is, however no question that the information obtained from such records is more useful and reliable than that resulting from methods previously described.

B MEASUREMENT OF ACCOMMODATION

Methods described in Section A have been concerned with the use of electric shocks where the application was sudden and the rate of rise very high In addition to intensity and duration of a stimulus, there is another factor which determines its effectiveness and this is the rate of the rise of the wave-front.

If a stimulus of gradually increasing intensity is applied to excitable tissue, a very high value may be reached before excitation or triggering of response takes place. Living tissue has the power of adapting or accommodating its polarized structure to a gradual strain in such a way that a shock sufficient to cause excitation if applied suddenly may be quite inadequate if the peak of the

stimulus is reached over a period of time thus the threshold value for ex by a *gradually increasing or progressive, stimulus* may be many times than the threshold for a sudden stimulus. The ratio of these threshold v a measure of the accommodation of a tissue. The accommodation po *nerve fibre are much greater than those of muscle alone and* as Bordet pointed out, this fact can be used to distinguish innervated from den muscle.

Accommodation measurement as a diagnostic procedure has been litt in this country and the concept and methods are unfamiliar but a nun workers (Solandt 1935 1936 Kugelberg, 1944 Pollock, Golseth, *Sherman, Schiller and Tigay 1944 1945 Pollock, Golseth, Arieff and M* 1945) have described techniques and series of case records

There are a number of methods which while all basically dependent assessment of accommodation, *differ sufficiently to justify separate descr* It should be noted that accommodation while innately related to the st of nerve and muscle and to excitability characteristics in general n special methods for its measurement *it cannot be deduced directly fr* curve recordings

(i) *Galvanic tetanus Ratio*

This test involves the production of sustained contraction in mus continuous galvanic current This is to some extent an unphysiologic cedure, but it has the advantage of simplicity in that the ordinary g current can be used without modification. The rheobase is first determine is, the threshold excitability of the muscle to a sudden shock of abo second s duration A galvanic current is then applied through the electrodes and is gradually increased in strength until continuous contr takes place, when the value is recorded The ratio *current required to p tetanus rheobase* is of the order of five for normal muscle and less than t denervated muscle. No attempt is made in this test to measure or stand the rate of increase.

Provided that the sustained contraction is limited to a few seconds at n long enough to read the meter and no more—the procedure is reasonabl tolerated by patients, and is simple and rapid Nevertheless, the test is haza for the subject. It is one of the few diagnostic measures liable to produc burns because of the high and prolonged currents sometimes needed to pr contraction

(ii) *Progressive Current Testing*

Accurate measurement of accommodation requires a stimulus s capable of delivering a gradually increasing shock, where the period of ris *peak value at the threshold of excitation* can be recorded The configurati time of the rising wave front is of some importance. Currents that mc exponentially logarithmically or linearly may be used

It is not advisable to use a progressive-current method alone, that is to merely recording the threshold at which excitation occurs. If the rheoba the particular muscle is already high the excitation value to progressive cu may be extremely so The important index of accommodation is the *threshold for progressive current/threshold for sudden-shock excitation* ratio expresses the relative elevation of threshold when the stimulus is gra as opposed to instantaneous, and is a true measurement of accommodati

Commercial apparatus for this test is not available, but numerous circuits have been published (Solandt 1935 Kugelberg 1944 Osborne, Grodins Mittelman, Milne and Ivy 1944) which vary somewhat in their characteristics Solandt describes a simple arrangement for producing exponentially increasing shocks of relatively short duration (fractions of a second) which are suitable for normal nerve-muscle, but ineffective for denervated muscle except at very high intensities The other authors employ more complex and refined techniques, electronic in the case of Kugelberg and Grodins, and electro-mechanical in the instance of Pollock, for producing progressive current shocks of long duration (several seconds) with linear wave-points. Both Kugelberg and Pollock have published good reviews of the history and literature of this method Pollock *et al* (1945a) have published an important paper dealing with electro-diagnosis of peripheral nerve injury by such currents and this remains the principal source of clinical information

The method is not a simple one for routine testing there is some difficulty in determining the exact intensity for constant response, the muscular contraction being usually of a prolonged or tetanic nature when it occurs. The objection already made to galvanic tetanus ratio determination also applies here in that considerable currents may have to be applied for several seconds it frequently happens that the stimulus has to be repeated a number of times to check the observations, and care is required to avoid tissue injury

Although little employed in this country the claims made for the accuracy of a long-duration progressive-current diagnostic test are impressive and will be considered later The method must be considered seriously as an important contribution to electro-diagnosis.

(iii) *Alternating Current Intensity-frequency Curves*

In so far as duration of stimulus and rate of rise of its attack are both factors in excitation measurement, it is to be expected on theoretical grounds that stimulation with sinusoidal alternating current of variable frequency will demonstrate a definite optimum frequency for a particular type of tissue. This optimum occurs when the frequency of alternation is such that the combination of rate of rise and half wave duration balance out so to speak, in effectiveness. At frequencies below the optimum the rate of rise will be slow at higher frequencies the duration of each half-cycle will be short From the aspect of effective stimulation the two oppose each other

The application of variable-frequency AC to muscle and nerve and the measurement of the intensity required at each frequency reveals a frequency intensity relationship which shows a definite optimal frequency Currents of small intensity are more effective at this frequency than above or below it (Hill Katz and Solandt, 1936 Osborne *et al.*, 1944 Grodins, Osborne, Johnson and Ivy 1944) As the optimal frequency for minimum-intensity excitation is of the order of 60 cycles per second for normal, and 2 c./sec. for denervated human muscle the diagnostic possibilities of the method are evident Three factors have retarded the development of the method except in small-scale experiments. It is difficult and costly to procure an AC generator capable of delivering adequate power at the low frequencies needed for denervated muscle (0·5 to 5 c./sec.) The method involves continuous passage of current through tissues and the risk of burning is a real one at high intensities, for although excitation depends on frequency tissue heating does not. Thirdly the optimal frequency depends to some extent on the index of response, powerful contraction of

denervated muscle requiring a higher frequency than perceptible response of the same muscles (Grodins, *et al* 1944) It is doubtful if this latter observation represents a serious objection in careful diagnostic work, where the response is always small, but its bearing on the optimal frequency for therapeutic stimulation is most important. There are other minor technical difficulties, and the number of observations made in this country is insufficient to justify conclusions.

3 Identification of Neuro-muscular Complexes

It must be clearly understood that diagnostic electrical stimulation depends on differences in excitability between nerve usually in the form of its terminal fibres in muscle, and muscle itself since a denervated muscle lacks nerve fibres.

The distinction between normal and totally denervated muscle is clear-cut electrically but intermediate stages exist which are of great clinical importance. The most valuable diagnostic method is that which indicates these intermediate stages most reliably They occur in muscle which is partially innervated for example in partial nerve injury in certain stages of recovery in poliomyelitis, and in various other diseases of motor neurons and the spinal cord diseases. Similar intermediate stages are seen in muscles with two sources of innervation when one supply is interrupted. It is important to appreciate that the answer obtained by electrical methods to the question "What is wrong with this muscle?" *is given in terms of extent or degree of innervation and not in terms of* pathology

Local muscle stimulation has thus a very definite limitation, in that it is concerned only with the muscle and the presence or absence of nerve endings in that muscle, and not with the circumstances which may give rise to that absence.

The variety of technical approaches to the problem arises from the desire for quantitative methods, reproducible and comparable, which will yield as much information as possible, especially in the detection of partial degrees of innervation. The methods are all best used as follow-up investigations to compare figures on the same muscle from time to time and note improvement or regression rather than as spot diagnosis examinations.

The figures on which this report is based are taken from records of patients suffering from peripheral nerve injury during the 1939–45 war and a smaller number of cases thereafter The inevitable pressure of work during and after the war period, together with the uneven development of and interest in the various techniques (some of which have been greatly improved since) renders a complete comparison of their usefulness impossible. Many thousands of records of galvanic/faradic tests are available for analysis, many hundreds of intensity duration curves, and isolated examples of certain of the others. The author has had personal experience of all the techniques described and (on a limited number of patients only) has had opportunities of comparing them on the same subject. A number of workers have published records of employment of two or three such comparative tests (Doupe, 1943d Pollock *et al*., 1945a, b Pollock, Golseth, Arieff Sherman and Mayfield, 1945 Newman and Livingston, 1947).

There is much information therefore on these diagnostic procedures and this will now be presented in such a way that the excitability of various neuro-muscular complexes will be specified in terms of practical measurements. In a final section an attempt will be made to appraise in more detail those methods in which study of large numbers of records has been possible.

(i) *Normally Innervated Muscle*

The electrical excitability of normal muscle stimulated percutaneously can be defined as follows

a A brisk tetanic contraction (starting and stopping with the passage of current) to the output from the secondary winding of the usual faradic coils. An experienced operator can make a rough estimate of normal intensity by noting the degree of core insertion and the setting of the layer selector switch this estimate is not transferable from one coil to another and is a measure of experience rather than of faradism

In subjects who are thin skinned a muscle will occasionally respond to very weak currents but this has no diagnostic significance

Thick skin and oedematous or ischaemic tissues may prevent the excitation of muscle by faradic current with certain coils of inadequate maximum strength this confusing finding will be discussed later

A brisk tetanic response to faradism at reasonable intensities produced by standard physiotherapy coils is indicative of a normally innervated muscle This observation is one of the most valuable electro-diagnostic tests Muscle which responds to reasonable strengths of faradism and is nevertheless clinically paralysed is so from functional reasons, or because of neurapraxia it is not denervated

Muscle may respond to faradism, but be clinically paralysed in the sense of being too weak to produce movement of the part this situation arises because the electrical test gives no account of *amount* of innervated muscle, and a small innervated portion may be normal but too weak to do work.

b Normal muscle will respond to a condenser charged to a potential of 100 volts and caused to discharge directly through the electrodes most muscles will respond by one rapid twitch to the discharge of condensers of 0·1 mfd or less small and superficial muscles may respond to condensers as small as 0·01 mfd The results from repeated day to-day examinations of the same muscles are inconstant, and a range ratio of 5 to 1 may be expected The test is simple easier to perform and more quantitative than faradism but is inferior to more exact methods.

c Normal muscle shows a chronaxie which is remarkably constant The actual figure varies with the method used to determine it high impedance constant-current stimulators will give figures ranging from 0 15 to 0 8 milli seconds whereas low impedance instruments with known voltage output will give a range between 0·03 and 0·08 m sec. Ninety per cent of all observations on normal muscles in healthy subjects will fall within these ranges. The greatest deviation in observations carefully made on one muscle of one subject was of the order of $\pm$ 0 02 m.sec.

An exact relationship between the internal resistance of the generator and the chronaxie figure remains to be determined Preliminary investigations show that a high-impedance current source should have an internal resistance of not less than 100 000 ohms, a voltage stimulator of not more than 800–900 ohms In practice most instruments more than satisfy these requirements but one with an internal resistance between 1 000 and 100 000 ohms will give figures which will require careful interpretation and will not be comparable with those published

It should be noted that determination of chronaxie as a single index is obsolete the principal value of the index in clinical work being to serve as one

denervated muscle requiring a higher frequency than perceptible response of the same muscles (Grodins, *et al* 1944) It is doubtful if this latter observation represents a serious objection in careful diagnostic work, where the response is always small, but its bearing on the optimal frequency for therapeutic stimulation is most important There are other minor technical difficulties, and the number of observations made in this country is insufficient to justify conclusions.

3 Identification of Neuro-muscular Complexes

It must be clearly understood that diagnostic electrical stimulation depends on differences in excitability between nerve usually in the form of its terminal fibres in muscle and muscle itself since a denervated muscle lacks nerve fibres.

The distinction between normal and totally denervated muscle is clear-cut electrically but intermediate stages exist which are of great clinical importance. *The most valuable diagnostic method is that which indicates these intermediate* stages most reliably They occur in muscle which is partially innervated for example in partial nerve injury in certain stages of recovery in poliomyelitis, and in various other diseases of motor neurons and the spinal cord diseases. Similar intermediate stages are seen in muscles with two sources of innervation when one supply is interrupted It is important to appreciate that the answer obtained by electrical methods to the question, What is wrong with this *muscle?' is given in terms of extent or degree of innervation and not in terms of* pathology

Local muscle stimulation has thus a very definite limitation in that it is concerned only with the muscle and the presence or absence of nerve endings in that muscle, and not with the circumstances which may give rise to that absence.

The variety of technical approaches to the problem arises from the desire for *quantitative methods, reproducible and comparable, which* will yield as much information as possible, especially in the detection of partial degrees of innervation The methods are all best used as follow up investigations to compare figures on the same muscle from time to time and note improvement or regression rather than as spot diagnosis examinations.

The figures on which this report is based are taken from records of patients suffering from peripheral nerve injury during the 1939–45 war and a smaller number of cases thereafter The inevitable pressure of work during and after the war period, together with the uneven development of and interest in the various techniques (some of which have been greatly improved since) renders a complete comparison of their usefulness impossible. Many thousands of records of galvanic/faradic tests are available for analysis many hundreds of intensity duration curves, and isolated examples of certain of the others. The author has had personal experience of all the techniques described, and (on a limited number of patients only) has had opportunities of comparing them on the same subject. A number of workers have published records of employment of two or three such comparative tests (Doupe 1943d Pollock *et al.*, 1945a, b Pollock, Golseth Arieff Sherman and Mayfield 1945 Newman and Livingston 1947).

There is much information therefore on these diagnostic procedures and this will now be presented in such a way that the excitability of various neuro-muscular complexes will be specified in terms of practical measurements In a final section an attempt will be made to appraise in more detail those methods in which study of large numbers of records has been possible.

(i) *Normally Innervated Muscle*

The electrical excitability of normal muscle, stimulated percutaneously can be defined as follows

a A brisk tetanic contraction (starting and stopping with the passage of current) to the output from the secondary winding of the usual faradic coils An experienced operator can make a rough estimate of normal intensity by noting the degree of core insertion and the setting of the layer selector switch this estimate is not transferable from one coil to another and is a measure of experience rather than of faradism

In subjects who are thin skinned a muscle will occasionally respond to very weak currents but this has no diagnostic significance.

Thick skin and oedematous or ischaemic tissues may prevent the excitation of muscle by faradic current with certain coils of inadequate maximum strength this confusing finding will be discussed later

A brisk tetanic response to faradism at reasonable intensities produced by standard physiotherapy coils is indicative of a normally innervated muscle. This observation is one of the most valuable electro-diagnostic tests Muscle which responds to reasonable strengths of faradism and is nevertheless clinically paralysed is so from functional reasons, or because of neurapraxia it is not denervated

Muscle may respond to faradism, but be clinically paralysed in the sense of being too weak to produce movement of the part this situation arises because the electrical test gives no account of *amount* of innervated muscle, and a small innervated portion may be normal but too weak to do work

b Normal muscle will respond to a condenser charged to a potential of 100 volts and caused to discharge directly through the electrodes most muscles will respond by one rapid twitch to the discharge of condensers of 0·1 mfd or less small and superficial muscles may respond to condensers as small as 0·01 mfd The results from repeated day to-day examinations of the same muscles are inconstant and a range ratio of 5 to 1 may be expected The test is simple, easier to perform and more quantitative than faradism, but is inferior to more exact methods

c Normal muscle shows a chronaxie which is remarkably constant. The actual figure varies with the method used to determine it high-impedance constant-current stimulators will give figures ranging from 0·15 to 0 8 milli seconds whereas low impedance instruments with known voltage output will give a range between 0·03 and 0 08 m.sec Ninety per cent of all observations on normal muscles in healthy subjects will fall within these ranges The greatest deviation in observations carefully made on one muscle of one subject was of the order of $\pm$ 0·02 m.sec.

An exact relationship between the internal resistance of the generator and the chronaxie figure remains to be determined Preliminary investigations show that a high impedance current source should have an internal resistance of not less than 100 000 ohms a voltage stimulator of not more than 800–900 ohms. In practice most instruments more than satisfy these requirements, but one with an internal resistance between 1 000 and 100 000 ohms will give figures which will require careful interpretation and will not be comparable with those published

of 4 to 6 The use of the polar formula is not advised in normal muscle the cathode as active electrode may be of the order of four or five times as effective as the anode. If constant current is passed for long enough to allow of the observation of a break twitch the response may be observed by the development of galvanic tetanus, due to the very high intensity at make It should be noted here that if the primary circuit of an induction coil is completed and broken (as may be done to obtain isolated as opposed to tetanising shocks) for purely technical reasons the impulse at break from the secondary winding is much larger than that at make this effect must not be confused with the make and break responses of galvanic current.

f Normal muscle shows the power of accommodation by its response to a gradually rising or progressive current. Solandt (1935) stimulating the ulnar nerve at the elbow with exponentially rising current of relatively short duration found accommodation slopes lying between 12 and 24 and this applies also to stimulation of normal muscle individually that is through the nerve fibres in it, but with an electrode placed directly over it.

Pollock *et al* (1945a) after extensive experiment on animal preparations employ for man progressive currents of two durations only namely one second and four second rise periods. For practical testing some such simplification is necessary They show that a threshold slope of constant gradient (in which case actual duration of current within wide limits would be unimportant) can be observed in frog preparations, but not in cats or in man. The ratio requisite peak intensity for progressive current to sudden shock rheobase is not the same for all durations of progressive current, and with rate of rise, peak intensity and total duration as three associated variables, the operation of the method and the expression of its results become extremely complex for clinical work It may well be that during the passage of currents of such prolonged rising time ionic and fluid shifts occur in the tissues which by local alteration in current distribution obscure the constant gradient that is demonstrable in simpler preparations.

Pollock and his co-workers do not give figures for the normal accommodation index of muscle repetition of his technique in a series of 40 different muscles in four healthy subjects gives ratios progressive current intensity/rheobase of between 4 and 6 for a duration rise of one second and of 6 to 11 for a wave-front of four seconds duration The deviation of a series of observations on the same muscle of the same subject is disappointingly large and is in part due to difficulty in assessing a standard magnitude of response It is probable that this source of error could be overcome by simultaneous action potential recording, as described by Doupe (1943d) Ratios of less than four were never found though occasionally a very high ratio of the order of 18 or 20 was noted from normal muscle The effect of altering temperature and blood flow appears to be considerable.

The technique requires development and standardization on a statistically significant series of normal human muscles.

g Normal muscle when tested by variable frequency sinusoidal alternating current, shows a response to 50–60 c./sec. which can be elicited at lower intensity than for any other frequency higher or lower It is noteworthy in this connexion that 50 c./sec being the usual power line frequency in this country it is as effective and dangerous a current for causing accidental electrocution as could well be selected

The optimum frequency point on an intensity frequency curve is not sharp

and the threshold in general varies only about 20 per cent between 20 100 c./sec. The test is not an easy one to apply Patients are intoleran continuous AC stimulation and the risk of tissue damage cannot be ign If the current is gradually increased (at any frequency) from zero to thres tetanus develops so gradually that it is most difficult to assess a standard de of contraction without elaborate mechanical aids. On the other hand i current is applied suddenly random effects will arise because of the exact p at which the current is applied to the tissue the current may be zero or in either direction or much more commonly some intermediate value

It appears from experiment that without considerable development, e in the way of recording muscular tension or in respect of electronic ke of the sinusoidal burst so that it commences at zero current, the method practical difficulties it has not been used extensively in this country

(ii) *Denervated Muscle*

a Denervated muscle is for practical purposes unresponsive to fa current, though this statement must not be taken literally Denervated mu can always be made to contract by faradic current if the strength is suffici the patients toleration of the procedure and the available output from the are the limiting factors.

It is essential to appreciate that there is no sharp distinction between no and denervated muscle in their response to faradic stimulation it follows f a study of the Intensity Duration relationship that even very short shocks excite if they are strong enough With an insensitive subject or one who is u anaesthesia and with an induction coil whose output is of higher voltage t usual or whose individual pulse chances to be long on account of the elect constants in the circuit denervated human muscle can quite often be mad contract. This is a not uncommon pitfall in electro-diagnosis unless the oper appreciates the background of electrical testing. Thus the statement that abs of faradic response is indicative of denervation requires qualification. Mu which will not respond to faradic current as normally applied and tolerated patient and operator is most probably denervated. Several errors have b observed which arose from this misconception of the inexcitability of denerv muscle to faradism It is true that the response, which is tetanic, is slugg developing and relaxing slowly but this is often overlooked in the observat that the muscle contracts at all

Denervated muscle responds to the relatively prolonged shock of the galv current. In order to measure the rheobase the duration of current or volt must be at least 300 m sec (CT) or 100 m.sec. (VT) the use of longer sho than these will give identical intensity threshold figures, but will cause unnec sary discomfort. The response of the denervated muscle differs from the sud twitch or brisk tetanic contraction of normal muscle, and is exhibited a sluggish worm like contraction under the test electrode, often quite localiz Relaxation is prolonged after the stoppage of current.

The actual value of the rheobase is dependent upon various tissue conditio quite apart from size, position and depth of muscle concerned horny sk oedema and impaired cutaneous blood supply are the principal factors.

Over a large series of patients examined with 100 m.sec. VT shocks, a range rheobase values between 10 and 60 volts may be expected This is in agreem with general experience, and is rather greater than the range to be encounte—

in normal muscle 60 per cent of observations will give a rheobase lying between 20 and 40 volts. It has been noted by a number of reliable workers that denervated muscle has a lowered rheobase and this hyperexcitability was described as typical of the Reaction of Degeneration by Erb in 1868 On the other hand examination of several hundred case records of quantitative electric stimulation of denervated muscle in this country during the 1939–45 War shows this lowered rheobase to be an exceptional finding and this has been confirmed by personal communication with most of the operators concerned Although the lowered rheobase is recorded by many as a valuable diagnostic sign (particularly in respect of its increase when neurotization begins) analysis of the British records does not bear this out Further investigation requires to be made of this aspect of galvanic excitation of denervated muscle.

b Denervated muscle responds to 100-volt condenser discharges if the condenser size is of the order of 1 mfd or more, though this is only true of 60 per cent of denervated muscles examined systematically by this method It is found by extensive trial that condenser discharges fail to excite many muscles which respond to galvanism, and it is probable that the inter-electrode resistance is too low in these cases for the shock to have an adequate excitation time. The use of very large condensers (8 to 32 mfd.) and the use of a higher potential than the standard 100 volts overcomes this but makes the test as complicated as ID testing (in fact converts the method into a form of ID test) and is not justified as a single method for reliable diagnostic work.

c The chronaxie of denervated muscle varies between 0·9 and 4 m.sec. (VT) 12 to 50 m.sec. (CT) and is of the order of 20 to 100 times as great for that of the corresponding innervated muscle stimulated by the same technique. The figures are reliable, and less subject to environmental variation than any other single index

d The intensity-duration curve for denervated muscle is steeply inclined for durations below 100 m.sec. each reduction in shock duration calling for a considerable increase in the intensity required for threshold response. The threshold becomes so high for the short-duration pulses that response to the shortest is not usually obtained. The contrast with the ID curve for normal muscle is very obvious (see Fig. 153)

e A galvanic tetanus ratio approaching unity is characteristic of full denervation the muscle behaving as a contractile substance bereft of powers of accommodation. As a rheobase shock of the order of one second duration is required initially and very little increase will produce indefinite tetanic persistence of contraction the procedure requires care in the discernment of the minimum degree of response. It is not easy to distinguish the protracted sluggish twitch of denervated muscle from the tetanic state as both develop slowly and locally under the electrode

f Progressive-current testing confirms the galvanic tetanus ratio in a more quantitative manner and in the denervated state the ratio progressive-current intensity/rheobase (for currents of several seconds duration) approaches unity The authorities on this method believe that careful and experienced determination of the galvanic tetanus ratio is as good a practical diagnostic measure as the more elaborate progressive-current testing, particularly as *no* specialized apparatus is needed

g Denervated muscle responds to the smallest threshold intensity of alternating current when the frequency is in the range of 0·5 to 2 c /sec.

As already pointed out, this is technically difficult to achieve without the use of rotary contactors or resistances and in point of fact is true only for minimal degrees of contraction. Denervated muscle responds best in the sense of maximum developed tension with minimum discomfort, to 18 to 20 c./sec. AC, although its intensity frequency curve may show a rheobase in the 1 c./sec. region

(iii) *Partial Innervation*

The accurate identification of partially innervated muscle is the aim of all refined modern electro-diagnosis. Such a state occurs in the early stages of degeneration and in the recovery period It will also of course be apparent in lower motor neurone diseases such as poliomyelitis

Certain basic anatomical and physiological considerations complicate the problem, the chief being the anatomical relationship of innervated and denervated portions of a muscle with respect to the overlying skin and thereby their relative accessibility to electrical stimuli. As the criterion of excitation in ordinary electro-diagnosis is *visible or palpable muscle movement, small* innervated portions of a large muscle which chance to lie on the deep aspect may not be detected by stimulation Moreover because of the relative excitabilities of innervated and denervated muscle, a small fasciculus of denervated muscle underlying normal muscle is unlikely to be detected by percutaneous stimulation As the re innervation of a muscle after any nerve injury producing degeneration is bound to be a random process in the important early stages, it follows that electrical prognosis will sometimes give misleading results. An estimate of the proportion of cases falling into this category can only be made by statistical examination of a large series

In the second place electrical recovery bears no relationship to return of *voluntary power* A small amount of superficial innervated muscle may be electrically normal without having the power to perform useful work, for this depends on the total number of innervated motor units. The value of electro-diagnosis in partially innervated neuro-muscular complexes lies in its detection of re-neurotization before motor recovery appears to an extent detectable by clinical means. Certain techniques have proved more efficient than others, but in discussion the limitations just referred to must be borne in mind.

The reaction of partially innervated muscle appears transiently during degeneration, when its identification is relatively unimportant. Muscle undergoing re innervation passes through the stages from complete denervation to the final state achieved this may of course be a permanent condition of partial innervation, at least until such time as the denervated fibres undergo fibrosis.

a A partial reaction of degeneration is described for galvanic faradic testing. The muscle shows diminished faradic excitability and in its response to galvanism shows a sluggish type of contraction The condition is very rarely found in practice. Out of 1 100 galvanic faradic test records examined partial reaction of degeneration was reported on seventeen occasions as definitely present, and when deliberately sought for in muscles known to be partially innervated (as assessed by other methods) it was demonstrable in only 6 per cent of cases. As already emphasized, denervated muscle will respond to intense faradism, and the test is quite useless without a knowledge of the characteristics of the coil employed, and the intensity tolerated by the particular subject. A report of P R.D should not be accepted as significant without confirmatory evidence.

b The condenser-discharge test is unreliable for identification of partially innervated states, as the normal error range (of the order of 1 4) may overlap the intermediate zone between denervated and innervated ranges.

c The use of chronaxie as a single index for describing the partially denervated state has proved disappointing. Analysis of 92 cases followed from denervation to recovery shows that as neurotization proceeds the chronaxie does not necessarily change gradually from a high to a low figure but usually remains high until a sudden reduction signifies a considerable degree of recovery often detectable by clinical means alone this agrees with observations made by Pollock *et al* (1945a) A theoretical explanation of why a single chronaxie figure cannot express partially innervated stages can be deduced from study of the complete ID curves, which are not of a simple nature, and do not have a true chronaxie as originally defined.

d Intensity-duration curves from partially innervated muscle show certain characteristic features, the most important being the appearance of kinks or discontinuities. This observation was first made by Adrian in 1917 and has been amply confirmed by subsequent work (Pollock, Golseth and Arieff, 1944). It seems probable that a kinked curve represents two quantitatively different excitable substances.

The appearance of discontinuities in the ID curve is a very early sign of neurotization, and usually precedes clinical recovery by a considerable interval Nevertheless, they are not invariably observed because of the chance that the parts of a muscle undergoing re innervation may be either very scattered in the early stages or too deep relative to the whole muscle bulk to be accessible to the stimuli. There appears to be no significant difference in the relative value of VT or CT methods but it appears desirable, perhaps essential to use rectangular voltage or current pulses of rapid rise and fall

ID curves taken with exponential condenser discharges do not exhibit minor discontinuities A theoretical treatment of this subject is given by Bauwens (1941a) and his conclusions have been confirmed by direct comparison of condenser-discharge and rectangular-shock curves taken successively off the same muscles

Apart from discontinuities, a reduction in the general level of the ID curve from the denervated one, and a flattening of curvature is indicative of neurotiza tion. This has been many times reported with all types of ID curves (Marble Hamlin and Watkins, 1942 Ritchie 1944) and is very evident in the present analysis. It is to be noted that if the statement above is true, and it has been confirmed by examination of several hundred muscle records an increase of rheobase is not an indication of neurotization (p 251)

As re innervation proceeds, the ID curves return towards the normal in shape and elevation the discontinuities disappear usually at rather an early stage, sometimes before voluntary power returns.

Attempts to express the complex ID curve of partial innervation by a single mathematical index are not successful Either they show no intermediate values, as in the case of chronaxie, or as in the instances of the Lassalle Index and the Lewy Index are too variable to be reliable in demonstrating minor discontin uities. Graphical plotting of the complete ID curve is the only satisfactory method of expression.

e Muscle in the early stages of neurotization is said to show a rise in the galvanic threshold, and an increase of the galvanic tetanus ratio from the

near unity figure This alteration of the ratio occurs before voluntary recovery and is a valuable sign of recovery Clinical findings will be discussed in the next section

f Similar observations apply to progressive-current testing. The author does not agree that the threshold to galvanism increases, but there is no doubt that a rise of progressive-current threshold/rheobase ratio indicating an increase in the accommodation powers of the neuro-muscular complex, does occur at an early stage in regeneration

g Except for a few isolated observations no information is available on the frequency intensity curve of partially innervated muscle It is not established whether the shift from denervated to normal optimum frequency occurs suddenly or gradually or if it precedes clinical recovery

(iv) *Fibrosis of Muscle due to Ischaemia or Prolonged Denervation*

Since degrees of muscle ischaemia are sometimes associated with peripheral nerve injury certain observations are relevant here. In severe degrees of ischaemia the contractile substance may be almost totally absent, in which case no electrical stimulation of any kind can be effective. But subjects with minor degrees of muscle ischaemia are often sent for electrical examination the reports are liable to cause confusion, yet these are the only cases in which examination is worth while

a Ischaemic muscle responds to intense faradic stimulation and to strong galvanic shocks with a contraction which is unlike the denervated response. The contraction may be localized but in its time-relations is normally more like the normal muscle twitch Absolute reaction of degeneration should never be reported on such a result alone.

b Ischaemic muscle has a normal type of ID curve, but it is usually impossible to plot the complete curve or to measure chronaxie, because of the very high threshold intensities required. Ischaemic muscle is identified by the observation that if it contracts at all (the rheobase may be very high) it will contract without increase of threshold when the shock duration (VT) is reduced from 100 m.sec. to 10 and even to 1 m.sec.

The problem of determining whether or not contractile substance exists is very often important in the absence of ischaemia as, for example, in facial paralysis of long standing for which surgical repair can be contemplated only if contractile muscle substance still persists In such cases any residual muscle will be not only denervated, but more or less fibrotic. In such cases a stimulator of the VT type is desirable, as the low impedance voltage wave is less painful to the patient than the CT shock (Ritchie, 1948) If contraction cannot be elicited at fairly high intensities (100 m.sec. duration 60 to 70 volts) there is a strong presumption of complete fibrosis. If the patient is unable to tolerate intensities of that order (a common finding in children) the test should be repeated under anaesthesia before a decision is made.

The two types of response just described are commonly found in muscle which has undergone a very limited degree of recovery after denervation this partially fibrotic state is seen as a terminal stage in muscles when no further recovery is to be expected and appears to be permanent. Weakness, high threshold of short or long duration and a rapid type of response, is the final state of poorly innervated muscle

4 Validity of Assessment

In any study of electro-diagnostic methods the chief aim is to ascertain from actual case records how much information can be obtained and with what degree of certainty Having now discussed the principles and general techniques of the methods available, it becomes possible to assess their value in practice Several thousand electro-diagnostic reports have been studied but only a small proportion of them yields significant information It will be realized that the records have been taken in different ways, by different operators and with different instruments, and on patients whose injuries, treatment and ultimate degree of recovery were extremely varied For final analysis drastic condensation of material is essential

One limitation emerges from a study of the records. There appears to be no significant difference in the electrical excitabilities of different muscles in respect of their innervation or anatomical position. Certain muscles are, of course more accessible to stimulation than others some nerves are known to give better clinical recovery after injury than others and in general the proximal muscles of a limb recover better after high nerve injury than those situated more distally

Nevertheless, the electrical excitability of human voluntary muscle, normal or denervated remains relatively unaffected by its local position It is not, therefore, necessary to discuss muscle groups as innervated by particular nerves, except in certain special circumstances. Further as electro-diagnosis is always carried out on an anatomical basis, the muscles being examined in their order of innervation this procedure can be taken for granted signs of recovery will naturally be sought in the muscle anatomically likely to recover first, and after they have been demonstrated there, similar signs altered only in degree will appear in more remote muscles if the recovery process continues satisfactorily

Though remote muscles may not show an ultimate degree of clinical recovery comparable with that of proximal ones, the signs of electrical recovery that they exhibit are the same. It is necessary to discuss only the excitability changes as found in muscle, regardless of site, provided that ordinary anatomical considerations are borne in mind

The second simplification that has been made is to analyse in detail only records from cases in which it has been possible to follow the electrical behaviour of muscle from the denervated stage to finality Since few cases reached the Nerve Injuries Centres immediately after injury the number seen during the first weeks after injury has been small and in any case the information is of secondary importance.

In the third place, most British records are based on two techniques only—the galvanic faradic test, and the registration of ID curves it has therefore been thought desirable to include a summary of contemporary American clinical results from progressive-current testing.

The course of recovery has been studied in detail in 700 muscles from 126 patients examined both by galvanic faradic and ID curve testing All these muscles were electrically examined at regular intervals and just over 5 000 records of individual single muscle tests are available for this group The findings fall into two groups statistically significant observations which can be expressed in quantitative terms, and a number of impressions with regard to muscle-testing which cannot be subjected to analysis. Finally certain important errors and anomalies, sometimes due to defective technique and sometimes due to uninformed interpretation, remain to be discussed

No attempt is made to reproduce the protocols from which conclusions are drawn as these are essentially graphical in the case of ID curves, their complexity and bulk are very great.

(I) *The Galvanic-faradic Test*

The standard method of charting muscle tests, whereby muscles supplied by a given nerve are listed in order of innervation, and assessed in terms of voluntary power faradic response and galvanic response, is very satisfactory since the progress of electrical and of clinical recovery are shown side by side.

Recovery of voluntary movement precedes that of faradic excitability in 60 per cent of the number studied the latter is therefore unreliable as a harbinger of clinical recovery Once voluntary movement has been detected, faradic excitability is usually reported within a few days and where a faradic response appears before voluntary movement, the interval is never longer than three weeks. There appears to be an important personal factor in these observations, because in 107 instances where a faradic response was reported to have preceded voluntary movement, *only three operators were involved in the reverse situa*tion a much larger number of testers were concerned. There is a very strong *suggestion that certain individual muscle testers can detect a faradic response* before voluntary movement, while others cannot. This is, after all, likely to be the case, as an operator with the personality to push the faradic intensity (possibly with a strong coil) may conceivably get a contraction which a weaker stimulus fails to produce. The results of muscle testing depend to a considerable extent on the skill and experience of the tester and this is borne out by comparing the results obtained by student physiotherapists with those of more experienced operators.

In such a large series of observations common errors became apparent, *especially as in all cases selected the complete course of recovery electrical* and clinical was later known

A faradic response is frequently reported from muscle known by other means to be denervated (ID curves post-operative interval ultimate failure to be re-innervated) In eleven cases certain muscles were repeatedly reported as being faradically excitable at times when they were undoubtedly denervated. The observation is of course correct, and is indeed a tribute to the operator's skill in preparing the patient and administering strong faradism but the incorrect interpretation (that the muscles are necessarily innervated because they respond *to faradism) is most misleading*

Occasional claims that faradic excitability precedes voluntary recovery by a *period of more than fifteen to twenty days are almost certainly due* to the same misunderstanding.

There was no evidence that any of these cases was either particularly sensitive to motor stimuli or insensitive to the discomfort of faradism, nor did the tester report that unusually high intensities were employed. However discrepancies appear in these records in that when the muscles were tested by one person they were reported "faradic response retained but on several examinations a different physiotherapist failed to confirm this.

As this confusion arose in 9 per cent of the cases analysed, and did so moreover in reports from the most skilled and experienced operators, it is one which should be borne in mind The report of voluntary power in the absence of *faradic response is common* Large muscles which acquire poor ultimate power frequently show this condition for many weeks a small number permanently

This is presumably due to the electrical inaccessibility of the innervated fibres it is not important prognostically, because once voluntary power has appeared it alone becomes the real criterion of progress.

Retention of faradic response in the absence of voluntary movement occurs in several conditions notably mild pressure palsies functional paralysis and mild degrees of ischaemia but this analysis is primarily concerned with its appearance in muscle paralysed from true denervation

The faradic excitability of muscle should not be relied on as a criterion of innervation as a single piece of evidence in the difficult or doubtful case its value is small The value of a report depends greatly on the skill of the examiner one sufficiently experienced to employ the test well would be better employed in studying and applying some more exact method The prognostic value of faradic testing is poor in that it does not give advance information of neurotization as compared with careful clinical examination for motor power

With regard to the use of galvanism the observations are usually of less practical importance If no complicating condition of the skin or blood supply is present, muscle, normal or denervated, ought to respond to galvanic shocks adequately applied this is usually borne out in practice. It is not usual to test a muscle with a galvanic current if a faradic response has just been definitely recorded because experience has shown that the galvanic shock will almost always be effective. The few recorded exceptions arise from the subject s intolerance to the long galvanic shock the common method of applying continuous current to a key electrode and making and breaking the current by the switch on the electrode handle is most uncomfortable for the patient because the duration of the on period of current is much greater than is necessary Most automatic interrupter devices also give a needlessly long and uncomfortable shock.

Denervated muscle sometimes appears not to respond to galvanic shocks Provided that the skin is in good condition and well prepared, and that no extensive muscle fibrosis exists the report implies that adequate intensity was not or could not be applied Contractile muscle tissue, if accessible always responds to galvanic shocks of sufficient strength though an anaesthetic may be required to demonstrate this

In normal galvanic faradic testing, the quantitative threshold of the galvanic shocks is not recorded it is therefore not possible to use the present series of reports to determine whether or not a true hypersensitivity to galvanism persists throughout denervation and disappears on neurotization "Hypersensitivity to galvanism" in the usage employed in normal muscle test reports appears to refer to sensory intolerance, which may be confusing. A large proportion is so reported and enquiry from patients invariably shows a marked distaste for galvanic stimulation This is true even for those with denervated and anaesthetic skin and the cause of the discomfort is not understood.

In 14 per cent of subjects "absent galvanic response" was reported in certain muscles at one time or another during their denervation period. Such a report is of no significance unless accompanied by a note of the intensity used recovery took place in the end in all the muscles concerned and contractile tissue was obviously present throughout Such a report is most likely to be made on the larger muscles, probably because a localized sluggish contraction is less easy to detect (there being no joint movement) than when the same amount of contraction occurs in, say the first dorsal interosseous muscle. The skin overlying denervated muscle is often thickened or oedematous from immobilization or

associated injury this both impedes the passage of current and makes detection of a response difficult While they persist such tissue conditions render muscle testing of very little value.

Two cases, having shown galvanic response throughout the period of denervation recovered voluntary power without any galvanic response, but with faradic excitability This anomalous finding is rare and need not cause confusion the patients are highly apprehensive of galvanic testing, and the operator will judge very definitely that the test is not valid and that the failure of galvanic stimulation is due to the subject's hypersensitivity

Failure to respond to galvanic shocks is indicative of cutaneous thickening, oedema, or muscle ischaemia in practice sensory tolerance is an important limiting factor and total absence of galvanic response should be accepted only after a test under anaesthesia. From this analysis of galvanic-current testing it is *not known what quantitative threshold changes if any take place during the* recovery period, but evidence from the long-duration rheobase shocks used for ID curve recording suggests that true lowering of the threshold to galvanic shocks is not a characteristic of denervation, and that when re-innervation occurs the rheobase gradually alters from a high figure to normal. This statement agrees with observations published by previous workers (Laroquette, 1920).

(ii) *Intensity-duration Curves*

In this analysis the recovery course, electrical and clinical of 700 muscles in 126 patients has been followed by means of observation of intensity-duration curves. The greater proportion of these curves was registered with a VT square-wave technique but comparison with the CT results shows no significant difference in diagnostic efficiency The method was introduced primarily as a quantitative method of assessing neuromuscular excitability experience and study of the records, together with experimental work on normal human muscle, shows that such tests to be of value must be conducted with an exact discipline.

The distinction between normal and denervated muscle is so straightforward that no in single instance out of the 5 100 curves examined has confusion arisen. In 1 720 ID curves recorded from muscles known to be completely denervated, on seventeen occasions only was the result equivocal and in these cases no definite response could be elicited at all that is to say where a curve can be recorded from denervated muscle *it will always reveal the denervation*

In a small percentage of cases, 1 per cent in this series, it may be impossible to record a curve, even with careful technique, and there is a strong presumption of ischaemic complications when this occurs.

Apart from any other advantages the technique may possess, these figures indicate that in about 99 per cent *of muscles examined a distinction between* normal and completely denervated muscle may be made with certainty If nothing more than this is required, the method is simpler and quicker to *perform than the galvanic faradic test.*

The recognition of degrees of partial innervation demands, however a thoroughly scientific approach, and the full value of the method can be developed only by regarding the procedure as comparable with say an electrocardiogram. The analysis shows that the results reported by an uninterested and uninformed tester compare very poorly with these registered by one interested in the problem as a piece of clinical research

In view of the factors affecting quantitative figures it will be appreciated that if ID curve testing is to be done at all it should be treated as a specialized

problem and not as a routine, particularly as much information still remains to be elicited by the application of the method to neuro-muscular disorders.

Re-innervation is indicated by two alterations in the typical curve of denervated muscle, namely the lowering and flattening of the curve, and the appearance of a kink or discontinuity in the curve, the latter being the better and more reliable of the two Earlier work (Ritchie 1944) was limited to the detection of general alteration of the curve because of the use of an inadequate stimulator which in consequence of an attempt to compromise between simplicity of operation and unnecessary precision, provided only five durations of stimulus, covering the range between 0·01 and 100 m.sec. (VT type) (Fig. 154) These five-point curves do not reveal minor discontinuities, and at least eight or nine different duration points should be used for each curve. This makes the recording and plotting of these curves a time-consuming process, but in the author's opinion this is unavoidable, since a review of all the earlier five point curves shows suggestions of kinks which might have been rendered definite by more detailed plotting. The design of precision stimulators has been greatly improved in recent years and a series of cases so examined has been published by Wynn Parry (1953)

In 69 per cent of the 700 muscles examined, ID curve kinks appeared before voluntary movement a figure which could probably be improved by better technique

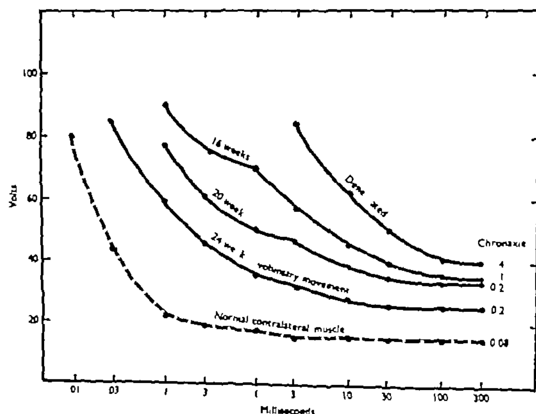


FIG. 154 The electrical course of recovery Voltage-Time curves from abd. poll. longus muscle after radial nerve suture in upper arm (Case 411 IER) Curves recorded with a ten-point duration scale, showing typical lowering and flattening of curves as re-innervation proceeds discontinuities may be missed if all points are not carefully recorded Electrical/clinical recovery interval 8 weeks in this example. Curves shown are selected from weekly records.

The interval between the earliest appearance of electrical recovery and the first signs of voluntary movement is extremely variable. Twenty-four per cent of these muscles showed no interval that is electrical and clinical recovery coincided 5 per cent showed definite voluntary movement before electrical recovery and in no case did substantial power develop unaccompanied by electrical evidence of recovery In 2 per cent electrical recovery was not followed by appearance of voluntary movement.

It has proved very difficult to determine the conditions in which a long interval between electrical and clinical recovery may be expected this interval is of course the very observation which renders the method of prognostic value. Nevertheless, a certain pattern is evident in the series of observations, though it is not immediately obvious from analysis

The long electrical-clinical recovery interval is particularly apparent in two types of muscles

(*a*) those supplied by a nerve whose composition is chiefly motor in particular the radial and facial nerves.

(*b*) those which are distally situated with respect to the nerve lesion, in contrast with muscles that are re innervated early

Combinations of these two types exist. The longest recorded intervals (over 100 days) have been from peripheral muscles (thumb extensors) supplied by the radial nerve, and from the first dorsal interosseous muscle supplied by the ulnar

Unfortunately these findings tend to diminish the prognostic value of the method since muscles supplied by the predominantly motor nerves are known to recover better than these supplied by mixed nerves and in the distal limb muscle recovery is so long delayed after neurotization has been amply demonstrated proximally that the observation of incipient electrical recovery may be only of academic interest. Moreover in most cases the recovery of small and distal muscles after repair of a main nerve is a matter over which one has little or no control

Muscles which are late in recovering and remain feeble often show a long interval so the latter appears on the whole to presage a poor result. The small number of cases of lesions in continuity examined have all shown very short electrical-clinical muscle recovery intervals These results of analysis are somewhat disappointing, for they are unfortunately the only ones that can be regarded as statistically significant. It does not appear possible to compare the recovery courses of one nerve with those of an anatomically different one, or to compare individual muscles except as above.

In 483 muscles showing an electrical-clinical recovery interval the mean interval was 29 days the longest 121 days 80 per cent of the observed intervals fall between 18 and 15 days This mathematical figure must be modified for prognostic use by the considerations discussed above. It is almost completely true to say that the detection of discontinuity in the curve of a muscle means that re innervation has begun the muscle will probably show voluntary movement within a month, but if movement has not appeared within that time the ultimate recovery will probably be poor The muscle will not necessarily recover movement at all, especially if it is situated distally and is supplied by a mixed nerve ID curves obtained under favourable conditions can demonstrate amounts of innervated muscle too small to produce useful movement (2 per cent of those examined)

The detection of regions of innervation in a matrix of denervated muscle must depend very largely on muscle bulk and the random chances of local

innervation Accessibility to electric shocks is a primary necessity for identifying such re-innervated portions indeed unless percutaneous stimulation can be supplemented by a technique of local stimulation by needles, or by electromyography anomalies are bound to appear in any series of records.

Yet it appears beyond question that valuable information can be gained from ID curve testing. However reliable information can be obtained only by the exercise of great care and accuracy in work, at least so far as early detection of recovery is concerned

(iii) *Progressive Current Testing*

Pollock, Golseth, Arieff and Mayfield (1945) describe the results of the examination of over 50 peripheral nerve injury cases When electrical signs of recovery appeared, the later course of events confirmed their validity in all but seven cases, in five of which information was not forthcoming. Only two cases presented equivocal findings. In all the cases that were diagnosed electrically as denervated the observation was confirmed by other means Pollock and his co-workers believe that a very high accommodation ratio or a very high galvanic threshold appearing from a muscle assessed as denervated (low ratio low threshold) are indicative of regeneration, and their results show this to be a valuable practical observation They do not give a detailed account of the electrical-clinical recovery interval except to comment that the longest observed interval was 150 days.

In a later paper (Pollock *et al* 1945b) they express the opinion that determination of galvanic tetanus ratio is probably diagnostically as effective, and practically simpler

Newman and Livingston (1947) comparing simultaneous records of ID curves, note that ID curve discontinuities appeared in 54 per cent of their cases and that the electrical-clinical recovery interval averaged 97 days 48 per cent of the same cases showed a rise of galvanic tetanus ratio averaging 109 days before clinical motor recovery Taking the two tests together a reliable prognosis was given in 73 per cent of cases.

(iv) *Technical Factors Influencing Electro-diagnosis*

In the previous sections reference has been made to the principal factors causing anomalies and errors both in recording and interpretation In order to obtain reliable diagnostic curves the purely technical aspects of stimulus application have to be considered especially in connexion with ID curve recording. Many of these remain to be worked out in detail but a number of points arise from the analysis of records

a For accurate ID curve recording, and especially for the identification of discontinuities, a stimulator capable of providing nine or ten different pulse durations (0·01 to 300 m.sec. VT) is necessary It appears probable that the low impedance voltage-calibrated type is easier to operate from the point of view of difficult patients, though the CT variety may require less preparation this point requires investigation.

b Skin resistance must be minimized by every possible means chiefly by washing, saline or electrode jelly being the two main contact agents used

c Limb temperature is of importance on the average a change of skin temperature of the order of 5 C causes a detectable alteration in rheobase values.

d Electrode size must be standardized and a unipolar technique is normally used with a circular electrode 1 cm in diameter The correct placing of the

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d Electrode size must be standardized, and a unipolar technique is normally used with a circular electrode 1 cm in diameter The correct placing of the

electrode is important. With normal muscle the motor point is usually quite sharply located whereas denervated muscle has no motor point and must be superficially explored with a view to detecting sensitive regions.

e A slow repetition rate for stimuli of the order of one shock per second, appears to render isolated twitches more readily detectable by touch or sight than the tetanic type of contraction produced by trains of impulses this is especially true for denervated muscle, where contraction and relaxation are sluggish

f Each ID curve should be recorded at least twice, working upwards and downwards through the successive duration shocks without shifting the test electrode.

g A curve taken with comparable preparation and care should always be registered from the corresponding contralateral muscle, since this procedure affords the best guarantee of good technique. It is noticeable that variations in the factors referred to all tend to alter the level of the record, but not its curvature, and therefore not its chronaxie. For this reason alone it is worth while to compute the chronaxie, although as a single index expressive of a given curve it is inadequate to show up discontinuities.

5 Summary and Conclusions

The primary deduction from a study and analysis of electro-diagnosis in a large series of cases is that it is only worth doing if it is done thoroughly and with understanding. It appears that the use of two different approaches to the problem would repay adoption in any unit or clinic which has to deal with large numbers of neuro-muscular disorders The first approach would be to replace the normal galvanic faradic outfit with a simpler stimulator delivering two different lengths of shock, of approximately 1 and 300 m.sec. respectively

To avoid the need for elaborate skin preparation this machine might well be of the CT high impedance type and if calibrated to a reasonable degree of accuracy (± 5 per cent) would avoid the pitfalls of the unmeasurable faradic output, and would be simpler quicker and less awkward to operate. It would distinguish with reasonable reliability between normal and denervated muscle and could be used for routine testing by any operator Denervated muscle would require a substantial intensity increase as between the long and the short shock, and normal muscle would not. The results could be easily recorded in the two-column chart already used for galvanic and faradic test reports.

In the second place, cases in which a series of measurements is desirable should be investigated in greater detail Precise electrodiagnosis should be regarded as the province of workers particularly interested in the procedures, and willing to regard the task as research and not as routine. As far as present knowledge goes, an examination consisting of (i) an ID curve based on from eight or ten readings and (ii) an accommodation measurement by galvanic tetanus ratio should give as much information about a muscle as we can hope to obtain from artificial stimulation These measurements are probably best done with a low impedance VT type instrument. Electromyography is a valuable adjunct. In three quarters of all recovering cases a combination of these methods should enable regeneration to be reported several weeks before detection of clinical recovery Extensive examination should be reserved for selected cases, since it is time-consuming and involves the use of complex apparatus. Many practical problems remain to be worked out, and the possibilities of electrodiagnosis have not yet been completely explored.

PART II ELECTROMYOGRAPHY

by RUTH E. M. BOWDEN

1 Introduction

FOR many years electromyography has been a recognized method of investigating the activity of voluntary muscle in health and in neuromuscular disorders both in man and the experimental animal (Adrian, 1925 Proebster 1928 Wachholder 1928 Adrian and Bronk, 1929 Pritchard 1929 and 1930 Lindsley 1935a b c and d 1936 Denny Brown and Pennybacker 1938 Hoefer and Putman, 1939 Hoefer 1941) On account of technical difficulties the use of electromyography was confined to experimental and clinical research workers but recent advances in the design of the apparatus have made it more generally available for routine clinical investigations It is therefore desirable to make some assessment of the place of electromyography in the diagnosis and prognosis of peripheral nerve injuries. Since this report is concerned with observations made in the centres established for treatment of these injuries the scope is necessarily limited and reference should be made to the work of others—among them Buchthal and Clemmesen, 1940 1941 1943 Buchthal 1949 Kugelberg, 1946 1947 1949 Kulgelberg and Petersen, 1949a, b and Denny Brown 1949—for observations in a wider field of neurology

2. Methods

(i) *Apparatus*

The apparatus designed by Weddell Feinstein and Pattle (1944) was used for the work reported here. Bauwens (1947) subsequently incorporated a meter calibrated in arbitrary units intended to give a measure of the activity of the muscles under investigation

Concentric needle electrodes were used (Adrian and Bronk, 1929) which were from 1 2 to 7 5 cm in length the diameters corresponding to International Standard Wire Gauge 20 to 26 Hypodermic needles were used for the outer electrodes and were mounted on cylindrical metal bases, fitted into 3-pin radio plugs. The muscles under investigation could be identified by stimulation down the needle electrode. In a few cases Weddell *et al* (1944) employed surface electrodes and later these were more freely used by Bauwens (1948)

The apparatus consists essentially of the electrode, a high grade amplifier and a loud-speaker unit. In the investigations reported here a cathode-ray oscilloscope was also employed and tracings were used for permanent records The loud-speaker unit is of particular value at the time of examination because small differences of duration and frequency are more easily detected by auditory than by visual methods. Furthermore, there are characteristic differences in the pitch of sounds associated with particular types of action potentials

Properties of the concentric needle electrode Weddell *et al* (1944) studied the marked directional properties and limited recording range of the concentric needle electrodes which they employed. The needle was adjusted until a motor unit action potential was recorded at its maximal amplitude. The bevel was kept facing the surface of the muscle and the needle was then rotated through 360 As the needle was turned slowly through 180 the amplitude of the action potential fell and gradually rose to the previous level as rotation was continued

through the next 180° If the needle was passed a millimetre or two below or above the epimysium no alteration was noted in the spike. This they concluded was an indication that there was no barrier effect due to the epimysium, but withdrawal of the needle 5 mm into subcutaneous fat caused the amplitude of the spike to fall to zero Movement of the needle in a direction parallel to the longitudinally arranged fibres of muscles such as the extensors or flexors of the wrist caused no alteration in the shape or amplitude of the recorded potentials. However movement from one quarter to 2 cm in a direction at right angles to the fibres caused a marked fall in the observed amplitude. In facial muscles there was a marked decrease in amplitude with small ranges of movement of the needle.

In another experiment the ulnar nerve was blocked in a healthy volunteer as soon as the Novocain had taken effect no motor units were found on attempted voluntary contraction of the paralysed muscles but the insertion type of motor units were elicited by movement of the needle (see p 265) As the needle was passed in various directions maximal voluntary contractions were performed by the unparalysed muscles and until the sheath of these muscles was reached or pierced no discrete motor units were recorded. They therefore concluded that no extraneous activity is picked up from neighbouring muscles when a concentric needle electrode is employed There was also evidence that the recording range of the electrode is limited from 1 to 2 cm. opposite the bevel. Brown (1937a) also determined the range and found it to be very restricted.

(ii) *Material*

Experimental Weddell *et al* (1943) studied the onset of fibrillation in the rat, rabbit, monkey and in a single human volunteer who submitted to an experimental crush of the nerves to brachio-radialis and extensor carpi radialis longus In the human case, a series of observations was made during the phases of paralysis and of recovery which was ultimately indistinguishable from normal by ordinary clinical examination

Clinical Patients admitted to the Military Hospital for Head Injuries at Oxford were studied by Weddell *et al* they were suffering from a wide variety of conditions normal volunteers were also studied In the Peripheral Nerve Injuries Centre at Oxford a systematic study was made of the electrical reactions and electromyographical changes in 130 patients with ulnar nerve injuries and in 46 with radial nerve injuries Many patients suffering from lesions of other peripheral nerves including the brachial plexus, were also examined

(iii) *Procedure*

The patients were placed in a comfortable position in a warm room with the muscles to be examined completely relaxed. Novocain (1 per cent) was injected intradermally over muscles to be explored with the needle electrode however many patients subsequently asked for this to be omitted as the rapid insertion of a sharp electrode caused less discomfort than the injection. It was found that as many as ten to twelve separate needlings could be done in the average service patient. If it was necessary to identify the muscles by stimulation the recordings were made first as a precaution in case any transient local damage was inflicted by the stimulus

3 Observations

A ACTION POTENTIALS IN HEALTHY VOLUNTARY MUSCLE

(i) *During Movement of the Needle Electrode*

In healthy limb muscles, the insertion of the needle electrode evokes an outburst which Weddell *et al* (1943) designated as insertion motor unit action potentials The outburst dies away rapidly and at an amplification of 2×10^4 no activity is recorded at rest. The insertion action potentials differ from the normal motor unit action potentials only in method of production Kugelberg and Peterson have investigated this activity more recently (1949b)

(ii) *During Voluntary Contraction*

On slight voluntary contraction 1 to 2 repetitive action potentials appear at the rate of 5 to 10 per second As the tension increases, the frequency of the action potential increases sometimes up to 50 per second this high rate was observed in only two out of 100 healthy subjects examined by Weddell *et al* (1944) the average maximum rate being about 20 per second With greater increases in tension, more action potentials appeared and ultimately the whole sweep on the oscilloscope screen was disturbed Simultaneous electrical and mechanical recordings were made in human muscles by Buchthal and Clemmesen (1941) and their paper should be consulted for full details of their observations. When a loud speaker unit is employed a characteristic low pitched rumbling sound is associated with motor unit activity During voluntary contractions of short duration no substitution of motor units was observed in the investigations reported here. In most limb muscles, the range of maximum amplitude of the potentials is between 100 microvolts and 2 millivolts and they are of 5 to 10 milliseconds duration Whilst the *maximum* duration and amplitude of an individual motor unit action-potential is constant, the duration and amplitude of different motor unit action potentials varies in the same muscle even with careful positioning of the needle. The average size of action potentials is greater in limb muscles than in the facial, lingual and laryngeal musculature and this is thought to be related to the number of muscle fibres which constitute each motor unit (Cooper 1929 Eccles and Sherrington 1930 Clark, 1931 Slauck, 1932 Wohlfart and Wohlfart, 1935 Buchthal and Clemmesen 1941)

The commonest form of action potential observed in a healthy muscle during voluntary contraction is mono- or di phasic, though a few triphasic and poly phasic potentials are found occasionally The appearance of the latter is some times simulated by pairs of di or triphasic action potentials which are firing almost synchronously However a short period of observation reveals the nature of these action potentials, which rapidly pass out of phase with one another Highly polyphasic action potentials are found most frequently during re innerva tion (see p 276) The occasional finding of true polyphasic action potentials in supposedly healthy muscles is possibly the result of localized minor damage to the nerve or muscle which has been followed by denervation and subsequent re innervation The sound of the true polyphasic action potential has a charac teristic explosive quality likened to the noise of an out board motor and this can be distinguished from the sound characteristic of simple motor units passing into and out of phase. True synchronous rhythmic discharges were not observed in healthy muscle in the investigations reported here. However Denny Brown (1949) and other workers have reported this phenomenon in supposedly healthy

muscle A rough assessment of motor unit activity can be made by observ the amount of disturbance of the time base tracing in a series of needlir Bauwens (1947) designed a meter by means of which some attempt is made make more precise readings however the value of this device has yet to substantiated fully

With a single-channel recording device it is possible to investigate the patte of normal voluntary movement to a limited extent, but the findings must interpreted with caution With a double or multiple channel recorder a m comprehensive study can be made (Floyd, 1949 Floyd and Silver 1950). T aspect of normal function has not been fully explored and it may explain so of the readjustments in the pattern of movement which are seen after injury peripheral nerves.

(iii) *At Rest*

With the apparatus used in these investigations no activity was recorded completely relaxed limb musculature of supposedly normal conscic individuals. However this inactivity was sometimes only obtained with effort apprehensive individuals, or in some alert and active persons. Weddell *et* (1944) showed that in certain trunk muscles complete relaxation was eit obtained with great difficulty or not at all. The muscles of the face and tong normally have resting action potentials but partial relaxation can be obtain with concentration after preliminary movements. In scalenus anterior and t abdominal muscles, there is a shower of motor unit activity during inspirati which fades to a minimum during expiration and is abolished with difficulty holding the breath

In laryngeal muscles, Weddell *et al* (1944) found that each inspiration a expiration is associated with showers of action-potentials and when the brea is held, constant activity persists whether the glottis is open or shut. With t exception of trapezius it was found impossible to abolish motor unit activity cervical musculature, but at rest complete silence was recorded in the lumb and thoracic portions of sacrospinalis

(iv) *Muscle Tone in Relation to Motor-unit Action-potentials*

Muscle tone has been defined in various ways. One of the more general accepted definitions was given by Holmes (1939) who stated that "to t clinician, tone generally means the constant slight tension characteristic healthy muscle which offers a steadily maintained resistance to stretching it recognized by the resistance experienced when the limbs are moved or displac passively" This broad definition was used a as basis for investigation of musc tone by Weddell *et al* (1944) They compared the electrical activity recorde from limb muscles with the mechanical resistance experienced when joints we moved or displaced passively

Observations In ten healthy subjects electrodes were inserted into extens carpi radialis longus. The forearm was supported on a table with the wrist ar hand hanging loosely over the edge. The subjects attempted to relax as complete as possible and the wrist was then rapidly flexed and extended by the observ All but one of the ten subjects were able to relax so that no motor-unit activi was recorded either at rest or during passive movement from any of th points sampled in the muscles. At the extreme range of passive moveme where discomfort was produced, activity was recorded, presumably due t

provocation of a stretch reflex. In six patients persuasion was necessary before this complete relaxation was obtained in three no persuasion was necessary In one subject described as of a nervous type, motor unit activity appeared whether the wrist was flexed extended or motionless As a result of clinical tests of palpation and displacement of the limb two of the three subjects who required no persuasion to relax were said to have reduced tone comparable with that encountered in cerebellar lesions the remaining eight were said to have normal tone Similar findings were made in the calf muscle and tibialis anterior Weddell *et al* (1944) concluded that tone of motor unit origin in normal limb muscles subjected to passive displacement was dependent upon the emotional or conscious level thresholds of the individual To overcome the objection that the sampling range was restricted surface electrodes and multiple channel recording with an electro-encephalogram ink writing apparatus was also employed the findings in the same ten subjects were confirmed Various pathological states were also investigated in an attempt to determine the factors responsible for normal and abnormal tone in voluntary muscle

B ACTION POTENTIALS IN DENERVATED MUSCLES

The first two notable contributions to knowledge of the action-currents in denervated voluntary muscle in man were made by Proebster (1928) and Denny Brown and Pennybacker (1938) The latter two authors identified the spontaneous irregular action-currents found in denervated muscle in man with the fibrillations found experimentally in denervated mammalian muscle. They suggested that this activity was due to sensitization of muscle fibres to small amounts of circulating acetylcholine. Experimental observations were made by Weddell *et al* and clinical observations of fibrillation were made in both the Oxford centres. Fibrillation action potentials are of two types those evoked by mechanical stimulation during the insertion of the needle electrode, and those which occur spontaneously and rhythmically and are wholly independent of attempted voluntary movement. Both types are heard as sharp clicking sounds in the loud speaker The action-potentials take the form of mono- or diphasic spikes 1 to 2 milliseconds in duration and up to 100 microvolts in amplitude and occur at rates varying from 2 to 10 per second without relation to voluntary effort These action potentials are found in wholly or partially denervated muscle whether the underlying lesion of the lower motor neurone lies in the cord as in poliomyelitis or in the periphery as in injuries or diseases of the peripheral nerves Where there is a partial lesion, several needlings may be necessary before the presence of denervated muscle fibres is revealed by finding fibrillation If the denervated muscle has undergone morphological change and has lost its power of contractility either as a result of advanced atrophy of denervation or necrosis due to an associated vascular injury no fibrillation action potentials can be found (Weddell *et al* 1944 Bowden and Gutmann 1949) Where the paralysis is due to an uncomplicated physiological block (neurapraxia) without degeneration of the nerve no fibrillation is found. However uncomplicated block of this type is exceptional, and a few fibrillation action-potentials are usually found if an extensive search is made.

The directional properties of the concentric needle electrode do not differ from those described earlier in relation to motor unit action potentials, but the recording range is even more limited when fibrillation is being investigated

In both man and experimental animals the onset of sustained fibrillation is preceded by the appearance of the insertion type of fibrillation action-potentials, and for a variable period the insertion type of motor unit action-potential is also evoked. In the experimental animal Weddell *et al* (1943) showed that the time of onset of fibrillation after denervation is related to its size and they suggested that this was due to differing metabolic rates In the peroneal muscles of the mouse fibrillation begins three and a half days after denervation, in the rat four days in the rabbit six and in the monkey eight days after denervation. The insertion type of fibrillation action-potential was found at correspondingly early periods. In thyroidectomized rabbits, in which the metabolic rate was lowered by about 30 per cent, fibrillation was delayed in onset and did not appear for about fourteen days There are no details of the numbers of animals studied and the range of variability in the individual species is not given.

In a single human volunteer an experimental crush injury (axonotmesis) was produced in the nerves to brachio-radialis and extensor carpi radialis longus (Weddell *et al* 1943 and 1944) In these two muscles the insertion type of motor unit action potentials could be evoked for a period of eighteen days after operation. The subsequent course of the case showed that the interruption of the axons supplying the muscles had been complete. Sixteen days after the operation fibrillation and motor unit action-potentials could be evoked by insertion of the electrode. On the eighteenth day no insertion type motor unit action potentials could be evoked, but the initial outburst of the insertion type of fibrillation action-potentials was succeeded by a series of spontaneous repetitive fibrillation spikes which varied in frequency from 2 to 20 per second From the eighteenth day onwards until re-innervation occurred no motor unit action-potentials were found It was concluded that although there was a complete degenerative lesion of the nerve fibres, the motor nerve-endings were capable of responding to mechanical stimulation for a limited period after the injury to the nerve trunk. Similar observations were made by Weddell *et al* (1943 and 1944) in other cases of injury to peripheral nerves In 25 cases needle electrodes were inserted into the sacrospinalis at varying periods after laminectomy had been performed for prolapsed intervertebral disc. A band of muscle was invariably found to be denervated. The insertion type of motor-unit action potential was found for twelve days following operation, and after ten days fibrillation potentials were evoked mechanically by insertion of the electrode by the twelfth day spontaneous repetitive fibrillation action-potentials were found. There was remarkable uniformity in the time course of onset of fibrillation in these 25 cases. It was observed that the average number and frequency of the spikes of fibrillation in sacrospinalis at four or more weeks after infliction of the injury to the nerves was greater than in limb musculature denervated for a similar period. (Quantitative data were not supplied.) It was suggested that the differences in the number frequency and time of onset of fibrillation action-potentials in sacrospinalis and limb muscles were related to the higher temperature of the more proximal muscles and possibly to differences in their metabolic rates.

The number and frequency of the fibrillation action-potentials may be increased by warming the limb and a similar increase was observed in a case of pyrexia due to sepsis. The injection of prostigmine also increases the number and frequency of fibrillation action-potentials. At the Wingfield Morris Orthopaedic Hospital it was observed that fibrillation action potentials were increased in number and frequency immediately after stimulation of the muscle through

the needle electrode They were apparently diminished by prolonged splinting and absence of physiotherapy and it therefore seemed worthwhile to investigate the influence of some of these factors on the time of onset of fibrillation Ten cases of recent degenerative lesions were investigated and the clinical data are set out in Table 59 (p 270) The influence of the age of the patient the position of the affected muscles in the limb the presence of one or more nerve injuries in the same limb and the influence of splinting and physiotherapy were analysed but it was evident that no reliable conclusions could be reached in this small series where there were numerous variable factors A larger number of cases is required In this small series the mean time of onset of fibrillation was 19 days S E. $\pm$ 2·0 for muscles of the arm 19 5 days S E. $\pm$ 2 36 for the muscles of forearm and 26 days S E. $\pm$ 2 5 for intrinsic muscles of the hand

Proebster s (1928) case showed fibrillation thirteen years after a birth palsy and in a similar case seen at Oxford fibrillation was found fifteen years after injury However as in both these cases partial recovery had occurred and the whole muscle was not denervated it is possible that the denervated fibres might have been maintained in an unusually good state Weddell *et al* (1944) found fibrillation eighteen years after an attack of poliomyelitis the activity was less than that found in recent cases of denervation and in some areas there were no signs of electrical activity either at rest or during voluntary effort This absence of activity was thought to indicate the presence of fibrotic changes in the muscle A few motor units were found in some other parts of the affected muscles. Weddell *et al* therefore concluded that the number and frequency of fibrillation action potentials showed no direct relation to the degree of muscle atrophy However there is no doubt that this activity diminishes with increasing duration of total denervation, for in severe atrophy the activity is feeble (Bowden and Gutmann 1944) It is probable that fibrillation will continue in denervated muscle as long as contractility persists (Tower 1939) At present there are no precise data to indicate the time limits, and there is no study of the exact relation between the structural changes in muscle and the cessation of fibrillation

C ACTION POTENTIALS IN PARTIAL AND PROGRESSIVE INTERRUPTION OF PERIPHERAL NERVES

There is as yet, no evidence to suggest that the time-course of fibrillation differs in complete and partial lesions In progressive lesions spontaneous repetitive motor unit action-potentials, uninfluenced by voluntary effort, are often obtained in addition to fibrillation This type of motor unit activity has been termed motor-unit irritability For example in three recent closed injuries, a closed dislocation of the hip a fracture dislocation of the shoulder and a severe blow on the point of the elbow intense spontaneous motor unit activity was found in some of the muscles supplied by the sciatic nerve the brachial plexus and ulnar nerve respectively In the third case, a complete degenerative lesion supervened and it is possible, although incapable of proof that an early transposition of the ulnar nerve might have averted the complete paralysis. The case certainly indicates the need for further studies of electromyographic changes in these types of injury When the anatomical position of the nerve renders it particularly vulnerable to repeated additional trauma surgical intervention might prevent the onset of a progressive degenerative lesion

Case no.	Age	Injury	Sepsis	Interval between injury and first E.M.G. (days)	Time of onset of insertion of fibrillation A.Ps. (days)
S.99	14	Ulnar nerve division	Mild	9 (E.M.G. silent)	12 23. Vigorous
S.78	24	Traction lesion brachial plexus Lt. (C5–6 complete. C7–8 also affected)	None	13	13. Very vigorous Deltoid Biceps Triceps E.C.D. F D.I. A.M.D
F 41	24	Lt. ulnar nerve division. Artery and F.D.S. cut	None	14	43 A M.D
E.19	23	Neuritis Lt. radial nerve, acute onset	None in arm but streptococcal dermatitis and adenitis. Carditis, ? due to streptococcal infection or rheumatic fever	20	20
A.36	17	Post interosseous paralysis after excision of head of radius	None	14. E.C.D. 15. A.P.L. and E.P.B.	14 E.C.D 15. A.P.L. and E.P.B.
J.25	20	Lt. lat. popliteal nerve Neurapraxia and axonotmesis. Dislocation of rt. hip	None	Less than 7	17 Tibial and peroneal group
E.6	26	Old traction lesion C 5 6, 7 superimposed median and ulnar partial axonotmesis after arthrodesis of shoulder	None	6. A.M.D. and 4th D I. 7 3rd and 2nd D.I. 9. F.D.I.	6. A.M.D. and 4th D.I. 7 A.M.D. and 4th D.I. silent. F.I. in 3rd and 2nd 9. F.D I., muscles became almost silent till 20th day when F.I. returned
A.35	29	Local damage to muscle branch	None Severe bruising locally	6. Complete silence of B.R.	
B 146	33	None	Cellulitis of arm	19 Silent A.M.D	
C.116	22	G S W radial nerve	Very slight		

Key to Tables 59

G.S W – Gunshot wound L.I.C. – Lesion in continuity, S – Suture F C.
irritability M U.A.Ps. – Motor-unit action-potentials. *Muscles* F C.
ulnaris A.M D – Abductor minimi digiti 4th D.I to F.D.I or 1st D.I. –
interosseus B.R. – Brachio-radialis E.C.R.L. – Extensor carpi radialis lo

59
fibrillation action potentials

Onset of fibrillation A.Ps. (days) Vigorous	Presence insertion M.U.A.Ps. (days)	Presence of M.U.A.Ps. (days)	Galvanism	Movements	Splinting
102. A.M.D	None found before operation		Nil at time of investigation	Active and passive to fingers	1st–50th days plaster-of-paris slab immobilizing wrist
26. E.C.D. anterior fibres of deltoid	F.D.I. and hypothenar	13. hypothenar F.D.I. flicker of vol. movement	Daily 5 days a week	Passive 4 times daily	Rest in bed with elbow flexed and shoulder flexed and abducted
	14. Present	Nil	Nil at first E.M.G. 5 days week from 15th day	Passive 3 times week from 15th day + active exercises	1st—21st days plaster holding wrist flexed
28. E.C.R.B., E.C.D	20. Triceps ++++	3/4 lose triceps	Daily	Daily passive + active exercises	Cock-up splint for wrist since paralysis
23. E.C.D A.P.L.	15 ? present E.C.D 18 Very igor ous	Nil close till recovery was possible 74 days after injury in E.C.D	Nil at time of investigation	Active only at time of investigation	Cock-up for wrist
	12. Tibial and peroneal group also on 17th	Nil at this period	Nil at time of investigation	Active + passive of knee and ankle 5 days	Back splint
41 A.M.D and 4th D.I	7 3rd and 2nd D.I. 8. A.M.D 3rd and 4th D.I 10. A.M.D D.I. 4-1	15. o w d sporadic but difficult to find and sometimes absent although there was a flicker of vol. power	Nil	Passive digits	Thoraco-brachial plaster spica
Not investigated after 24th day Patient discharged No sustained fibrillation found	Nil on 1st or 2nd E.M.G. in paralysed muscle		Nil	Active movements only of limb	Nil
	Nil	Nil	Daily from 16th day	Daily active + passive exercises	None to hand. Plaster to arm. Ulnar nerve splint later
	Present	Nil	Daily	Daily active + passive exercises	Cock-up for wrist

65 and Figures 155 to 163

Extensor carpi radialis brevis E.C.D = Extensor communis digitorum E.C.U = Extensor carpi ulnaris E.M.D = Extensor minimi digiti A.P.L. = Abductor pollicis longus E.P.L. = Extensor pollicis longus E.P.B. = Extensor pollicis brevis E.I. = Extensor indicis.

D ACTION POTENTIALS IN REVERSIBLE NERVE BLOCK (NEURAPRAXIA)

n non-degenerative lesions leading to paralysis which may last several weeks, ertion motor unit action potentials are invariably found and usually a few etitive motor unit action potentials as well The latter may or may not be ler voluntary control Fibrillation is absent. However in nearly all cases erred to the Nerve Injuries Centre there was some degree of denervation, ich was demonstrated by the presence of fibrillation action-potentials, the nber varying with the severity of the degenerative process. Weddell *et al.*

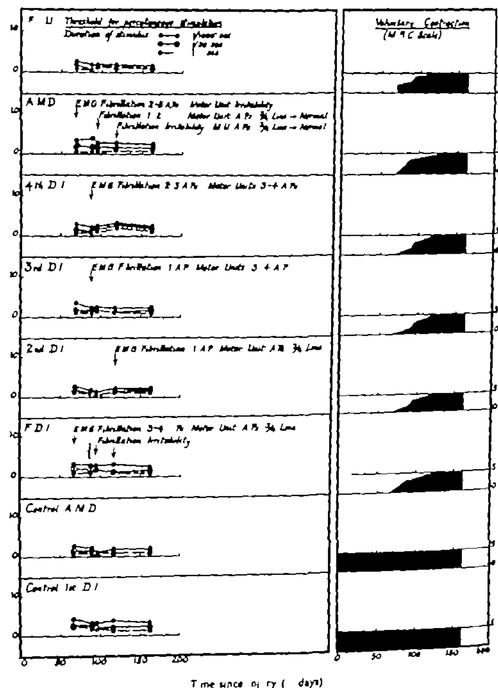


FIG 155 S.80 Neurapraxia of right ulnar nerve with minor degree of axonotmesis

A.M D
DURATION OF STIMULUS
1/1000 sec.
1/150 sec
1 0 sec
VOLUNTARY POWER
M R C Scale
Control A M. D
4th D.I
3rd D.I
2nd D I
E D.I
Control F D I
MILLIAMPS
DAYS
INJURY 13 cms above M E

Fig 156. B 158 Percutaneous electrical excitability Injury neurapraxia with some degree of axonotmesis.

(1944) published detailed reports of 75 cases of facial nerve palsy showing all degrees of damage from a complete uncomplicated block to complete degeneration of the nerve.

The electromyographical observations and results of electrical stimulation in three cases of neurapraxia with varying degrees of degeneration in the nerve trunk are shown in Figs. 155–159 In case S 80 (Fig. 155) the electrical reactions

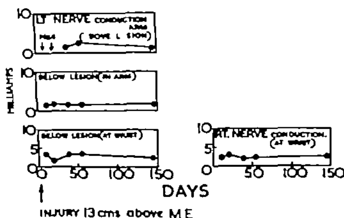


Fig 157 B 158 Nerve conduction

of the muscles were virtually normal nerve conduction was positive below the lesion but the threshold was a little raised. On the grounds of electrical stimulation an uncomplicated block was diagnosed but electromyography showed that there were a few fibrillation action-potentials, thus indicating a minor degree of degeneration in the nerve trunk. These denervated muscle fibres were either

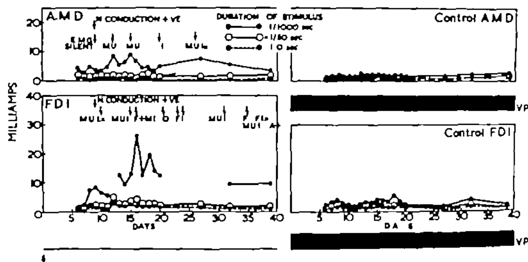


FIG. 158. E.6. Percutaneous electrical excitability Injury partial axonotmesis and neurapraxia, left ulnar nerve (? 50 cm. above pisiform).

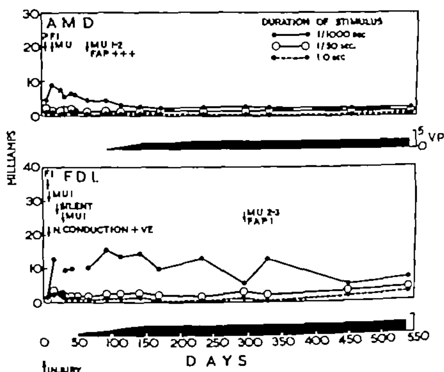


FIG 159 E.6. Percutaneous electrical excitability Injury partial axonotmesis and neurapraxia, left ulnar nerve (? 50 cm. above pisiform).

very few and scattered or so deeply placed as to be inaccessible to electrical testing. The amount of damage in the nerve was of no detectable functional significance and 160 days after injury clinical recovery was complete

In case B 158 (Fig. 156 and 157) a more serious degree of degeneration was suspected because the electrical reactions were significantly abnormal The progress of the case demonstrated that this conclusion was justified In case E.6 (Fig. 158) there were marked abnormalities in electrical reactions, particularly in the early phases. Although paralysis was complete for at least eight weeks in the first dorsal interosseous muscle, and for three months in abductor minimi digiti distal stimulation of the nerve trunk below the level of the lesion gave a positive result throughout the period of paralysis Motor unit action potentials of the insertion type were found, but it was not until the fifteenth day that a few were evoked by voluntary effort Fibrillation action-potentials of the insertion type were found on the sixth day By the end of the first week after injury it was possible to predict that some recovery would occur within about three months but in view of the marked abnormality of the electrical reactions a guarded prognosis was given and later the appearance of fibrillation confirmed the presence of large numbers of denervated muscle fibres. It will be seen in Fig. 159 that the progress of the case was slow and after eighteen months there was still gross weakness of the muscles.

E ACTION POTENTIALS IN RE INNERVATED MUSCLE

Weddell *et al* (1944) published the first report of a systematic study of action *potentials in re-innervated muscle in man. In their experimental case, they* followed the changes from time of injury to full recovery and they also report the changes found in other cases.

In both the Oxford Centres a decrease in the number of fibrillation action potentials was observed before the return of motor unit activity which was particularly striking where there had previously been vigorous fibrillation At variable times after this diminution in fibrillation motor unit action-potentials were recorded in response to voluntary attempts to move the paralysed part. *In the experimental case, fifteen days elapsed between the decrease in fibrillation* and the appearance of motor units in brachio-radialis, and in extensor carpi radialis the period of quiescence lasted nineteen days.

The writer studied the electromyographic changes and alterations in electrical reactions in a series of ulnar and radial nerve palsies. Bauwens constant-current stimulator was used It was observed that during the relatively silent phase and during the early stages of recovery of voluntary power the muscles became less excitable, the threshold currents being raised (cf p 253) The physiotherapists treating these patients also reported a decrease in excitability *It is* suggested that this rise in the threshold to electrical stimulation and the associated decrease in fibrillation action potentials may be related in some way to the return of chemical transmission at motor nerve-endings. Brown (1937a and b) found that intra arterial injection of acetylcholine increased the number and frequency of fibrillation action-potentials. Larger doses led to a diminution of fibrillation and later to complete electrical silence a contracture of the muscle developed and the threshold to electrical stimulation was markedly raised During the early quiescent phase of recovery after radial nerve injuries a shorten ing of the extensors of the wrist was demonstrable in a number of patients In spite of continued regular and vigorous passive exercises and physiotherapy the

range of passive flexion of the wrist joint decreased, and in some of the patients this shortening of the extensor muscles was persistent. There is more than a passing resemblance between these phenomena and those described by Brown. When motor-unit activity was re-established, fibrillation action potentials once more became vigorous, but decreased in number as further re innervation took place. In the experimental lesion Weddell *et al* (1944) found that fibrillation action-potentials could be picked up in some areas of the muscles for as long as twelve months after injury although there was no subjective or objective clinical evidence of weakness. Similar observations were made by the writer

The first motor unit action potentials which appear in response to voluntary effort are of low amplitude and tend to be repeated at rates of about 20 per second though at first they cannot be sustained for more than a few seconds at a time. Although there was no visible or palpable evidence of voluntary contraction, the patients frequently stated that they had some sensation of movement. Care was taken to question the patients before electromyography was performed so that they were not influenced by the result of the test. Weddell *et al* (1944) found that in early re innervation the injection of prostigmine appeared to facilitate neuromuscular transmission and the motor-unit action-potentials were increased in amplitude and sustained for longer periods

In the experimental case, it was observed that although successive examinations showed rapidly increasing numbers of motor unit action-potentials, the activity of some of these units could not be sustained continuously and the subject stated that he was aware that however hard he tried it was not possible to maintain the attempted movement at a steady level.

Action potentials appear first in the region of the motor point and can then be obtained in varying numbers throughout more distant parts of the muscle. The writer found that the first detectable action-potentials could be obtained as much as 8 cm below the motor point in some of the radial extensors, which may be some indication of the length of the constituent muscle fibres in a motor unit in a long fusiform or strap-like muscle.

The variations in amplitude and duration of the action-potentials of individual motor units are greater than normal In the early stages of re-innervation transient outbursts of the insertion type of motor unit action-potential may be difficult to distinguish from fibrillation particularly in facial muscles, where the motor unit action-potentials are normally smaller and of shorter duration than in limb muscles. The frequency of these small action potentials is usually not lower than 20 per second and this, along with the fact that they are produced by voluntary effort, serves to distinguish them from fibrillation action-potentials. These small motor unit action-potentials are usually associated with complex polyphasic spikes of medium or low amplitude (100 to 500 microvolts) in the other parts of the muscle. As many as twelve spikes have been recorded in a single polyphasic complex. The polyphasic spikes have a characteristic rough sound and although they may be evoked by voluntary effort, they occasionally continue firing when all effort has ceased Although polyphasic spikes are found in supposedly normal muscle, they occur in greater numbers during re-innervation. These complexes may be picked up and recognized on successive days, their frequency alters with increase or decrease of tension in the muscle, and during a prolonged contraction. They differ therefore from the phasic change found when two normal motor units are close together Polyphasic spikes were found eighteen months after operation in the subject who had an experimental

lesion Weddell *et al* (1944) considered that these complexes must be regarded as true motor unit action potentials and that they are the result of three factors working singly or together First, during re innervation it is possible that only some of the fibres in a motor unit are re-innervated Secondly all the nerve fibres going to the constituent muscle fibres of the unit may not have reached the same degree of maturation and therefore conduction time and delay at the myoneural junctions might vary and lead to lack of synchrony in the contractions of the muscle fibres Thirdly they put forward evidence suggesting that nerve fibres which originally supplied contiguous muscle fibres are scattered They observed that when such a polyphasic action potential was found passage of the electrode through the thickness of the muscle at right angles to the direction of its fibres produced no appreciable change in amplitude this is in striking contrast to their findings in healthy muscle. Polyphasic action-potentials appeared to be less numerous after lesions in continuity than after suture of a nerve. They concluded that in re innervation, the pattern of innervation is abnormal particularly after suture of a nerve and after some lesions in continuity there fore the motor units do not necessarily consist of bundles of contiguous muscle fibres. They considered that the scatter in space of these muscle fibres was least after lesions in continuity and the histological findings reported in Chapter VII support their conclusions. Their explanation of the polyphasic spikes found in healthy muscle has been considered already on p 265

(i) *Progressive Re-innervation*

In addition to the increase in the number of motor unit action-potentials in a given muscle there is evidence of serial re innervation of the muscles supplied by the regenerating nerve. A rough guide to the number of motor units (in an area sampled) is given by recording the proportion of the oscilloscope sweep which is occupied by the action potentials and photographic records may also be compared. Bauwens was able, by use of his meter to compare readings on successive examinations, and he considered that this device was a useful aid to prognosis. Marx (1948) has used the same technique and concluded that it was of practical value.

(ii) *Rate of Return of Motor unit Activity*

Since it is possible to follow the return of motor unit activity in a series of muscles supplied by the same nerve, an attempt was made to study the rate at which this activity returned The principles underlying measurements of rates of recovery are discussed more fully in Chapter I and it is therefore only necessary to consider some of the points briefly The rate of growth of the axon tips, and the rates of advance of recovery of function are different, though in man both fall with time and distance. It is therefore probable that the same will be true of the rate of return of motor unit activity which is the earliest sign of recovery of motor function. In the investigations reported in Chapter I it was shown that there was an initial delay before the apparent beginning of the process of outgrowth of the axon tips and before the onset of the process of recovery of function There is also some evidence to suggest that there is a second delay between the arrival of axon tips and the formation of functional connexions with the end-organs. Clearly then it is unsatisfactory to calculate *average rates of recovery* of motor function by dividing the distance between the lesion and the most distal muscle by the time taken for recovery to occur in that muscle. However unless a sufficient number of observations is made in

each individual case it is impossible to make a satisfactory graph and appropriate curve or regression line. Although it has been possible to p course of recovery of voluntary power there are insufficient data to u method for demonstrating the rate of return of motor unit activity It has fore been necessary to adopt the somewhat unsatisfactory expedient of ca ing the *average rate* of return of motor unit activity for each case in 22 c radial nerve injury For comparison the *average rate* of recovery of vol power has also been calculated The nerve was sutured in eleven cases, an

TABLE 60

Radial nerve lesions in continuity Average rates of return of motor-u action-potentials and voluntary power

Case no	Level of lesion* (cm.)	Average rate of return of M U.A.Ps. (mm./day)	Average rate of return of vol. power (mm./day)	Final recovery M.R.C. scale
E.19	18	2 24	1·67	M5
H 81	12	2 22	1·91	M5
P.49	30	1·02	0 6	M3 S4
J.29	29	1·45	0 8	M4 S4
C.118	20	1 58	1 21	M4 S2
G 77	18 5	1·45	1·02	M4 S4
C 125	15	1 84	1 1	M4 S3
H 110	14	1 34	1 26	M4 S3
B 191	9	0·97	0 81	M3+S3+
S 137	9	1 39	1 1	M4 S3
P 104	6	1 13	0 9	M3+S3+

* Distance of lesion above lateral epicondyle of humerus

For Cases Making Motor Recovery of Grade M5

Mean rate of return of motor-unit action-potentials = 2 23 mm per day
S.E. = 0 007

Mean rate of return of voluntary power = 1 79 mm. per day
S.E. = 0 122

For Lower Grades of Recovery

Mean rate of return of motor-unit action-potentials = 1 35 mm. per day
S.E. = 0 093

Mean rate of return of voluntary power = 0 98 mm. per day
S.E. = 0 061 mm. per day

was a lesion in continuity in the other eleven. The cases were taken as presented for treatment at the Oxford Nerve Injuries Centre and we examined by the same observer The intervals between successive examina ranged from 1 to 3 weeks according to circumstances the length of this int introduces a source of error for recovery may have occurred anywhere bet 1 to 21 days after the previous examination The data are set out in Tabl and 61 and as would be expected the rate of return of motor unit activity *always more rapid than that of recovery of voluntary power* Two of the le in continuity E.19 and H 81 made a motor recovery which was clinically pe

and therefore they may be classed as cases of true axonotmesis in the remainder of this group the lesions were probably mixed axonotmesis and neurotmesis since recovery was imperfect. The rates of recovery of function are highest in the two cases of axonotmesis In the remaining lesions in continuity the rates are not only slower but they show considerable variation The mean average rates of return of motor unit activity and voluntary power are 2 2 mm per day S E. = 0 007 and 1 8 mm per day S E. = 0·122 for the two cases of axonotmesis, and for the remaining lesions in continuity the rates are 1 4 mm. per day S E. = 0·093 and 1·0 mm per day S E. = 0·061 respectively The rates of recovery in cases H 81 and E.19 are significantly higher than those of the remaining cases. ($P<0·01$) (Sholl personal communication)

TABLE 61

Suture of radial nerve Average rates of return of motor-unit action-potentials and voluntary power

Case no.	Level of lesion (cm.)	Resection (cm.)	Delay before suture (days)	Average rate of return of M U A Ps (mm. day)	Average rate of return of vol power (mm./day)	Final recovery M R.C scale
B.84	20 6	3 7	192	1 87	1 17	M4 S3
P.35	18 0	3·0	217	1·05	0·94	M3 S3
L.41	14 5	5·3	233	1 38	1 12	M4 S4
B 145	14·0	2 2	70	1 31	0·81	M4 S4
B 63	12·0	1 5	283	0 94	0·73	M3 S3
G 47	12 0	3 2	231	1 11	0 98	M4+S3
H.53	11·0	3 5	292	1·0	0·79	M4 S2
F.26	10 0	5 7	263	0·81	0·42	M2 S2
B 77	8 5	3·0	127	1 33	0 93	M3 S3
L.47	5·5	3 7	180	1 31	0 93	M3 S3
R.55	2·4	6·3	57	1 32	0·77	M3 S2

Distance of lesion above lateral epicondyle of humerus

Mean rate of return of motor-unit action-potentials after suture = 1 22 mm. per day S.E. = 0 086

Mean rate of return of voluntary power = 0 87 mm. per day S E. = 0 062

No case of suture made a perfect recovery and again it will be seen that there is a considerable variation while some of these rates are comparable with those found in the lesions in continuity others are considerably lower The mean average rates of return of motor unit activity and recovery of voluntary power are 1 2 mm. per day S E. = 0·086 and 0·9 mm per day S E. = 0 062. The mean average rates of return of motor unit activity and recovery of voluntary power in the mixed lesions in continuity do not differ significantly from those found in the suture cases. ($P<0·05$) These observations are in accord with those made on the basis of the more satisfactory methods employed in the investigations reported in Chapter 1 The individual variations in the rates of recovery must be due to numerous factors, such as, for example, the level of the lesion in relation to the affected muscles, the length of delay before suture and the length of nerve resected. That some of the rates of recovery after sutur

TABLE 62

Radial nerve lesions in continuity Interval between return of motor unit action potentials and clinical evidence of recovery of voluntary contraction

Case no.	Age (yr)	Injury	Level of lesion above Lat Ep (cm)	Interval between appearance of M U A.Ps and voluntary contraction (days)										Final recovery M.R.C. scale	Galvanism	Notes
				B.R.	E.C.R.L.	E.C.R.B.	E.C.D	E.C.U	E.M.D	A.P.L.	E.P.L.	E.P.B.	E.I			
L 19	23	Strep. poly-neuritis	18	—	28	M.U.A.Ps and ? flicker simultaneous	14	Less than 14→ M.U.A.Ps and flicker simultaneous	—	14	—	—	56	M5	+	← No M.U A.Ps 14 days before
H 81	21	Closed fracture	12	Simultaneous→		—	1	21	—	Simultaneous	—	—	21	M5	+	← No M.U 21 days before
P 49	18	Traction	30	—	29	—	—	113	—	113	—	—	322	M3 S4	+	Posterior cord lesion
J 29	70	Disloc. of h me al head	29	—	—	33	—	—	—	76	—	—	255	M4 S4	+	
C 118	22	G.S.W	20	—	—	Simultaneous	42	41	—	41–62	—	—	72	M4 S2	0	
G 77	26	G S.W	18 5	Less than 40	49	35	70	Less than 35	—	56	—	—	103	M3+S2	+	
C 123	32	P e s from haematoma	15	—	—	—	150	Approx. 123	—	67	—	—	116	M4 S3	0	
H 110	33	G.S.W (fracture)	14	—	—	31	14→	—	—	13	—	—	—	M4 S3	+	←+ Insertion type M U A.Ps 41 days before vol. cont.
B 191	28	G S.W (fracture)	9 0	—	13	—	21	21	—	21	—	—	52	M3+S2	0	
B 137	26	G.S.W (fracture)	9 0	—	3	—	17	17	—	17+	—	—	49	M4 S3	+	
P 104	24	G.S.W	6 0	—	18	8	29	29	—	28	—	—	42	M3 S3	0	

N.B. Level of lesion determined by anatomical distribution of paralysis and by presence of neuroma and of Tinel' [illegible]

TABLE 63

Suture of radial nerve Interval between return of motor unit action potentials and clinical evidence of recovery of voluntary contractions

Case no	Age (yr.)	Injury	Level of suture above Lat. Epi. (cm.)	Length of nerve resected (cm.)	Delay before suture (days)	Interval between appearance of M.U.A.Ps and voluntary contraction (days)										Final recovery: M.R.C. scale	Galvanism
						B.R.	E.C.R.L.	E.C.R.B.	E.C.D.	E.C.U.	E.M.D.	A.P.L.	E.P.L.	E.P.B.	E.I.		
B 84	27	G.S.W. (fracture)	20·6	3·7	192	—	42	21	104	48–83	—	91	—	—	119	M4 S3	Irregular
F 35	21	G.S.W. (fracture)	18·0	3·0	217	No recovery branches sacrificed	21	29	94	66	—	17	—	—	51	M3+S3+	+
L 41	29	G.S.W.	14·5	5·3	233	—	14	—	—	56	—	43	—	—	—	M4 S4	+
B 145	31	G.S.W.	14·0	2·2	70	—	31	—	80	64	—	42	—	—	147	M4 S3	+
B 63	41	Compound fracture	12·0	1·5	284	272	158	147	126	132	—	41–45	—	—	90	M3 S3	0
G 47	26	G.S.W. (fracture)	12·0	3·2	231	66	66	22	43	43	—	21–49	—	—	77	M4+S3	+
H 53	23	G.S.W.	11·0	3·5	293	42	42	Less than 56	63	Less than 63	—	64	—	7 26	76	M4 S2	Irregular
F 26a	22	G.S.W. (fracture)	10·0	5·7	263	—	97	70	—	141	—	99	—	—	312	M2 S3	+
B 77	30	G.S.W. (fracture)	8·5	3·0	127	—	—	—	70	63	—	28	—	—	81	M4+S3	+
L 47	30	G.S.W. (fracture)	5·5	3·7	180	—	12	—	Less than 28	35	—	14	—	—	69	M3 S3	+
R 53	23	G.S.W. (fracture)	2·4	6·3	57	—	—	—	28	42	—	35	—	105	105	M3 S2	+

Key pp. 270 and 271

compare with those found in lesions in continuity is not surprising for there may be less intraneural scar tissue after a well-executed secondary suture than after an extensive lesion in continuity

(iii) *Interval between the Reappearance of Motor unit Activity and Return of Voluntary Contractions*

In their experimental case Weddell *et al* (1944) detected the first signs of voluntary movement two days after motor unit activity was first recorded in brachio-radialis. When the first flicker of movement was detected the number of action-potentials was small and activity was poorly sustained After ten days motor unit activity was sustained and within two months the muscle was capable of contracting against resistance. In extensor carpi radialis longus the interval between recording of action potentials and the first flicker of movement was nine days by the twelfth day the muscle was sufficiently strong to move the wrist when gravity was eliminated. In this type of experimental injury intraneural scarring is slight, and the axons therefore advance in an even wave down to their appropriate destinations, and a high degree of maturation is achieved. In other cases, Weddell *et al* found considerable variation in the interval

After suture of the motor division of the ulnar nerve at the wrist an interval of three to four months was observed between the recording of motor-unit action potentials and the first signs of recovery This variation in the length of the interval was attributed to several factors, amongst which were the abnormalities in the pattern of re innervation due to misdirection, obstruction and abnormal branching of the regenerating nerve fibres. In the intrinsic muscle of the hand abnormal branching of the nerve fibres would increase the difficulties of detecting feeble movements, for mass action occurs in two groups of small muscles with opposite actions. The anatomical position and function of the re innervated muscle is therefore significant, for it is often difficult to detect small degrees of movement clinically in certain muscles. Other factors are the atrophic changes in the muscles themselves which in turn are influenced by electrotherapy and splinting.

A second investigation of the interval between the return of motor unit activity and the recovery of voluntary contraction was made at the Oxford Nerve Injuries Centre The findings are given in Tables 62, 63 (pps. 280, 281) The shortest intervals were found in the two cases diagnosed as true axonotmesis Case E.19 is illustrated in Fig. 160 In the other cases of lesions in continuity the interval tends to increase in the more distal muscles, which might possibly be due to the more advanced atrophic changes in them In the cases of suture the variation of the interval in different individuals and individual muscles of the same case is more striking. Case B 63 is of particular interest for here there is a steady decrease in the interval in the more distal muscles (Fig. 161) Too much stress cannot be laid on this isolated case but it is perhaps significant that Aitken (1949) found that maturation proceeded more rapidly in nerve fibres travelling the longest distances. Although there appears to be a much shorter interval in true axonotmesis, (see E.19 and H 81) no consistent difference was found when comparing pairs of cases of suture and mixed lesions in continuity where the level of the injury and the final degree of recovery were similar (Table 64 p 284) Once more no satisfactory detailed analysis of the causes of variation is possible, owing to the small number of cases, and the variable factors.

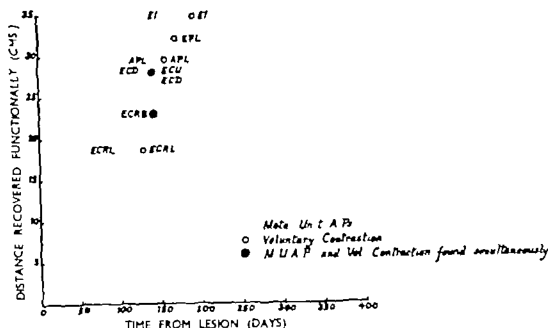


Fig 160 E.19 Return of motor-unit activity and voluntary contraction. Injury axonotmesis, radial nerve (approximately 18 cm. above L.E.)

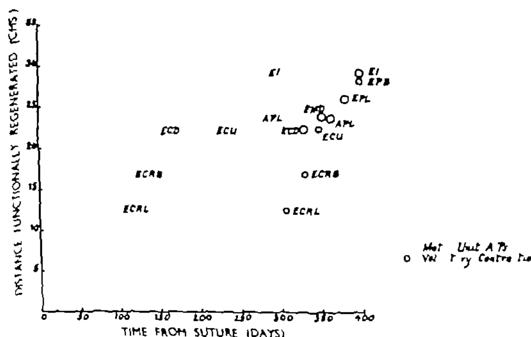


Fig 161 B.63 Return of motor-unit activity and voluntary contraction. Injury neurotmesis, radial nerve (suture 12 cm. above L.E. Delay before suture 224 days.)

Some cases of suture of the ulnar nerve are available for comparison with the series of radial nerve sutures (Table 65 p 285) However the conditions cannot be regarded as strictly comparable in the two series, for several reasons. Where the injury of the ulnar nerve is at or above the level of the elbow the distance between the site of the suture and the intrinsic muscles of the hand is considerable

TABLE 64

Paired data comparing intervals (measured in days) between the finding of motor unit action-potentials and first sign of voluntary contraction after suture and lesions in continuity of the radial nerve

	Case	Level (cm.)	Injury	Final recovery	E.C.R.L.	E.C.R.B.	E.C.D	E.C.U	A.P.L.	E.I.
1 Suture	B.84	20 6	G.S.W (fracture)	M4 S3	—	21	104	49-83	91	119
1 L.I.C.	C.118	20	G.S.W	M4 S2	—	Simultaneous	42	41	41-42	72
2 Suture	P.35	18	G.S.W (fracture)	M3+S2	21	21	94	66	17	51
2 L.I.C.	G.77	18 5	G.S.W	M3+S2	49	35	70	35	56	103
3 Suture	L.41	14 5	G.S.W	M4 S4	—	—	—	56	43	—
3 L.I.C.	C.125	15	Pressure of haematoma	M4 S3	—	—	—	123	67	—
4 Suture	L.47	5 5	G.S.W (fracture)	M3 S3	12	Less than 28	—	—	14	69
4 L.I.C.	P 104	6	G.S.W (fracture)	M3+S3	18	29	—	—	28	42

Distance of lesion above lateral epicondyle of humerus.

Key pp. 270 and 271

(approximately 30 cm from the level of the medial epicondyle of the humerus to the hypothenar muscles) Thus a considerable time must elapse before the regenerating axons can possibly reach the proximal group of intrinsic muscles. The total time of denervation of the muscles is therefore prolonged and atrophic change may be severe On the other hand if the nerve is damaged at the level of the wrist, the distances between the lesion and the intrinsic muscles of the hand are relatively small However it has been shown that the rate of advance of recovery of motor function decreases in the more distal segments of a peripheral nerve (Sunderland, 1947 1948 Bowden and Sholl 1950) This factor may therefore be of considerable significance when dealing with injuries at the level of the wrist or in the lower part of the forearm. It is possible that the total period of denervation of the muscles may be longer than might be expected at first sight. Since recovery of function is dependent on all the factors leading to functional completion of the nerve fibres, the process of maturation has to be considered as well as the actual advance of the regenerating axon tips. The slower rate of advance of recovery of function in distal segments of a damaged nerve might be due to increasingly slow maturation of the nerve fibres (but cf Aitken 1949) It is interesting to note that the period of decreased fibrillation was prolonged (1 to 5 months) in some of these cases of recovery after lesions at the level of the wrist In one case of a boy aged 14 years (S 99) the insertion type of motor unit action potentials were found consistently over a period of six months before any motor unit action potentials could be recorded in response to voluntary effort. Recovery was ultimately satisfactory in this case. These observations suggest that motor nerve fibres had been present in the muscles for at least six months before adequate functional connexions had been re-established.

Although the intervals between the appearance of action-potentials and recovery of voluntary contractions were prolonged in some of these cases of suture of the ulnar nerve, in others they were short and compare with those

TABLE 65

re of ulnar nerve Interval between return of motor unit action-potentials and clinical evidence of voluntary contractions *

ge r)	Injury	Level of suture in relation to pisiform (cm.)	Length resected (cm.)	Delay before suture (days)	Interval between return of M.U.A.Ps and voluntary contraction (days)					Final recovery M.R.C. scale	Galvanism
					A.M.D.	4th D.I.	3rd D.I	2nd D.I	1st D.I.		
2	G.S.W	+44·0	Extensive	341	—	No recovery of vol. power M.U.A.Ps present			91	M2+S2+	+
7	Laceration	+44·0	7·0	239	62	111	111	111	0–62	M2 S0	0
5	G.S.W	+40·0	9·0	351	—	265	265	265	18[illegible]	M2+S3	0
2	Incised	+30·0	3·7	121	—	108	108	136	92	M3 S3	+ Irregular
11	G.S.W	+30·0	5	109	140–228	228	—	311	140–228	M3 S3	+
4	G.S.W	+30·0	6·0	132	42	76	—	—	31	M3 S2+	+
26	G.S.W	+30·0	8·5	281	113	195	195	195	63	M3 S1	0
17	Laceration	+28·0	5·2	157	Simultaneous	132	132	132	132	M3 S3	+
22	Laceration	+24·0	2·1	100	81	195	195	195	302	M2+S3	+
38	G.S.W	+21·0	2·7	86	112	—	—	—	112	M2 S3	+
28	G.S.W	+16·0	2·8	161	91	133	133	133	185	M3 S3	+
24	G.S.W	+14·0	2·5	229	25	126	84	84	71	M3 S3	0
39	Laceration	+ 6·0	5·0	290	Simultaneous	—	—	—	Simultaneous	M3 S3	+
21	G.S.W	+ 3·5	2·8	127	42	42	—	—	42	M2+S3	0
28	Laceration	+ 2·0	1·0	63	4	42	42	42	85	M3 S3	+
45	Laceration	+ 3·0	2·5	219	123	M.U.A.Ps but no recovery of voluntary power			628 (at least)	M2+S3	0
35	Laceration	+ 2·5	No note	Primary	59	No definite recovery M.U.A.Ps present			285	M2 S2	+
13	Laceration	+ 3·0	3·0	62	160	—	239	239	239	M3 S3	+
23	Laceration	− 1·0	2·7	91	28	90	90	146	62	M3+S3	0
33	Laceration	+ 0·4	2·2	93	? simultaneous	84	84	84	84	M4 S3+	+
78	Incised	At P	2·3	151	Less than 61	75	172	172	172	M3+S3	0
20	Laceration	At P	2·4	178	101	140	140	225	38	M4 S2+	0
60	Laceration	A P	3+	128	3·1	—	—	—	—	M3 S3	+
33	Laceration	Below P	2·7	78	70	179	—	129	179	M4 S3+	+

All hands warmed for this investigation.

Long period of quiescence (6 months of denervated fibrillation with doubtful M.U. activity of insertion type).

Key pp. 270 and 271

found in the series of radial nerve sutures The length of this interval does not necessarily appear to be related to the final degree of recovery It is not felt justifiable to draw any definite conclusions from the available data, but it is clear that variation in the length of the interval is marked and this merits further investigation

(iv) *Relationship between Return of Motor-unit Action-potentials and Increased Excitability of Muscles to Percutaneous Electrical Stimulation*

The electrical reactions of muscles were tested at regular intervals in a series of patients with ulnar or radial nerve injuries. The technique was standardized and Bauwens constant-current stimulator was employed Square wave impulses were delivered the duration of stimuli were 1/1000 1/50 and 1 second, and the current could be varied independently up to 40 milliamps. In some of the patients, systematic electromyographic recordings were also made on the same day as the electrical reactions were tested (the data are given in Tables 66 and 67) In 62

TABLE 66

Relation between return of motor-unit action-potentials and return of excitability to percutaneous stimuli of 1/1000 second s duration during recovery from complete degenerative nerve lesions

	No. of cases
Return of motor-unit action-potentials before return of excitability	29
Simultaneous return of motor unit action potentials and excitability	20
Return of excitability preceding return of motor-unit action-potentials	3
Response to stimulus never lost during denervation	10*
Total	62

Threshold values were all markedly raised in comparison with control values in healthy muscles of opposite limb.

patients who were recovering from injuries which had led to complete Wallerian degeneration motor unit activity preceded the return of a response to a stimulus of 1 1000 second s duration in 29 cases and in 20 patients motor unit activity and the response to stimuli of *1 1000 second s duration* were found simultaneously (Successive examinations were made at intervals of several weeks in some cases) In only three cases did the response to stimuli of 1 1000 second s duration precede the return of motor unit activity However in 10 cases, the response to percutaneous stimulation (1/1000 second s duration) persisted throughout the period of denervation, although the threshold was

abnormally high The threshold was also high when the response to stimuli of 1/1000 second first returned As will be seen from Table 67 the improvement in excitability tended to precede the first signs of voluntary movement It is clear from Tables 66 and 67 that electromyography tends to give earlier evidence of regeneration of the motor fibres However it is important to stress the necessity for several successive examinations by electromyography and testing of electrical reaction for an isolated examination may prove most misleading.

TABLF 67

Relation between return of voluntary contraction and excitability of muscle to percutaneous stimuli of 1/1000 *second's duration during recovery from complete degenerative nerve lesions*

	No. of cases
Recovery of voluntary contraction preceding response to stimulus	12
Response to stimulus preceding recovery of voluntary contraction	44
Simultaneous recovery of voluntary contractions and return of response to stimulus	17
Response to stimulus never lost during denervation	9*
Total	82

Threshold values were all markedly raised in comparison with control values in healthy muscles of opposite limb.

(v) *Recovery of Independent Movements*

After suture or lesions in continuity of a nerve the presence of intraneural scar tissue leads to obstruction and misdirection of the regenerating axons This misdirection and abnormal branching of axons leads to loss or impairment of independent movements In many cases the defect is easily detected by inspection alone, but in some cases clinical examination is insufficient. Weddell *et al* (1944) pointed out the value of electromyography in the demonstration of mass or associated movements which follow various types of injury In a case of suture of the ulnar nerve they used the following technique to show the presence of such associated movements A double channel recording device was used and electrodes were placed in abductor minimi digiti and the first dorsal interosseous muscle of the affected hand When abduction of the fifth digit was attempted action potentials were recorded simultaneously both from abductor minimi digiti and the first dorsal interosseous. Attempts to produce isolated contraction of either muscle were invariably associated with outbursts of action potentials in both Further observations were made by the writer Only a single-channel recording apparatus was available. Readings were taken from

abductor minimi digiti during attempted independent abduction of the index finger and records were also made during attempted independent abduction of the fifth digit, when the electrode was in the first dorsal interosseous muscle. In all cases the hand was supported on a smooth surface with the palm downwards, and no active resistance was offered to the attempted movement. If no electrical activity was observed in one muscle during contraction of the other independent movement was graded as perfect' If one or two sporadic action-potentials were found the grading of good was given where more than half of the base line of the oscilloscope was disturbed independent movement was considered to be poor' In 63 cases of injury to the ulnar nerve, the normal hand was used as a control and the findings in these normal hands are set out in Table 68 In normal hands with perfect or good independent unresisted movements, this independence was lost when any degree of active resistance had to be overcome.

TABLE 68

(*A*) *Electromyographical investigation of independent movement in* 63 *normal hands*

Independent movements tested with E.M G	Hand		Total
	Right	Left	
Perfect	18	24	42
Perfect with concentration	5	1	6
Fairly good (1–2 M.U.A.Ps)	7	5	12
Fair to poor (½ to full line M U.A.Ps)	0	3	3
Total	30	33	63

Muscles tested were abductor minimi digiti and first dorsal interosseus muscles.

(*B*) *Electromyographical investigation of independent movement in* 47 *cases of sutures of the ulnar nerve*

In 47 cases of suture of the ulnar nerve recovery of independent movements was poor in every case

In 47 cases of suture of the ulnar nerve, independent movement was not found in a single patient throughout the period on although they were all receiving treatment and performing exer- to cultivate such move
ments This is of course, common cl It might be ted
that this defect in independent mo ult of weakness
of disturbance of innervation since it t independent
is normally when resistance has t However this
is ations made in types of case.
after a co iental block of e, moto
began to there was any of vo
e d that d d
Five ous innerv muscles

examined after complete injuries to the ulnar nerve The median nerve was found to supply some or all of the intrinsic muscles usually supplied only by the ulnar There were varying degrees of weakness of the affected muscles, but no defect of independent movement was found Forty cases of lesions in continuity were also investigated Of these, seven were ultimately diagnosed as cases of uncomplicated axonotmesis because motor and sensory recovery reached grade M5 S4 In one of the seven the nerve had been found to be free from signs of scarring when it had been examined at operation, and in another two the findings in biopsies of muscle supported the diagnosis Of the remaining 33 cases, 20 had palpable neuromata, and in the rest there was presumptive evidence of intraneural scarring since motor and sensory recovery were defective. Independent movements were perfect throughout the phase of recovery in three of the seven cases diagnosed as uncomplicated axonotmesis In two others independence was defective in the early stages of recovery but ultimately became perfect. In the two remaining cases independent movements were clinically described as perfect but electromyography demonstrated the presence of some defect, since a few motor unit action potentials could always be found in the muscle supposedly at rest. This defect was present throughout the period of observation after re innervation occurred

The 33 cases known or presumed to have some intraneural scarring showed significant abnormalities. In only two was there electromyographical evidence of complete restoration of independent movement. In three others independence was found in one of two muscles, and in 23 cases there was electromyographical evidence of poor independent movement although in some cases these move ments were described clinically as fairly good (Table 69)

TABLE 69

Electromyographical investigation of independent movement after complete degenerative lesions in continuity of the ulnar nerve

Independent movement tested with E.M G	No of Cases
Uncomplicated axonotmesis*	
Perfect	3
Perfect with education	2
Good	2
Total	7
Mixed axonotmesis and neurotmesis	
Perfect	2
Perfect in one but not in both muscles	3
Good, 1-2 M U.A.Ps	3
Fair	23†
Total	31

* Diagnosed clinically
† In 2 of these cases control muscles in normal hand showed poor independent movement.

Independent movements after partial degenerative lesions of the ulnar nerve were studied in eighteen cases. The left nerve was involved in ten cases and the right in eight. The data are set out in Table 70. The deterioration in two cases suggests that misdirection or abnormal branching of regenerating fibres had taken place.

TABLE 70

Electromyographical investigation of independent movements after partial degenerative lesions of the ulnar nerve

Independent movements tested with E.M.G.	No. of cases
Remained perfect from injury to recovery	1
Perfect in some muscles, deteriorated in others	1
Good	3
Improved from poor to perfect	2
Deteriorated perfect to poor	1
Fair to poor	10*
Total	18

In 2 of these cases control muscles in normal hand showed fairly good and poor independent movement.

TABLE 71

Summary of data presented in Tables 68 and 69

Independent movements	Condition of nerve				No. of cases
	Healthy	Sutured	Recovered axonotmesis	Mixed axonotmesis, neurotmesis	
Perfect to good	60	0	7	8	75
Fair to poor	3	47	0	23	73

These results were tested on the hypothesis that the proportions of those having perfect or good independent movements and those having fair or poor ones were the same for the different states of the nerve. This hypothesis was tested by the well-known method in which the ratio

$$R = \frac{\dfrac{T1}{N1} - \dfrac{T2}{N2}}{\sqrt{pq\left(\dfrac{1}{N1} + \dfrac{1}{N2}\right)}}$$

was calculated and referred to the normal scale.

T1 = The number of individuals in a sample of size N1 having a certain characteristic.
T2 = The number of individuals in a [illegible] of size N2 having the same characteristic.
$p = T1 + T2$

These studies of recovery of independent movement indicate that once abnormal peripheral connexions have been formed the central nervous system is unable to make the necessary compensatory adjustments to overcome completely the abnormal pattern of innervation Clearly on theoretical grounds it might be assumed that abnormalities of both motor and sensory re-innervation of muscles had been present However from this data there were no means of determining whether or not faulty re-innervation of muscle spindles had occurred Nevertheless, it seems legitimate to consider that the degree of independence which could be detected clinically was a measure of the number of fibres returning to their appropriate destination (Sperry 1945) The data are summarized in Table 71

(vi) *Recovery of Synergic Activity*

The recovery of synergic activity was followed in sixteen cases of radial nerve injury at the Oxford Centre. Six were lesions in continuity and ten cases of suture With the electrode in the radial extensors or in extensor carpi ulnaris, the forearm and wrist were supported to prevent flexion of wrist and movement of the needle, and the patient was then instructed to clench his hand The presence of action potentials during this movement provided evidence of synergic activity before there was any evidence of voluntary contraction in the affected muscles and in all cases clinical evidence of synergic action was found only some considerable time after the recovery of simple voluntary contraction These observations suggest that the late appearance of clinical signs of synergic activity is due to the relative weakness of the extensors of the wrist and not to a slow process of adjustment in patterns of neuromuscular activity Until the contractions in the extensors are sufficiently powerful to overcome the flexors, no clinical evidence of synergic activity will be found unless flexion of the wrist is prevented

4 Summary

(1) The electrical activity of healthy human muscle has been recorded by means of needle electrodes during passive movement of the appropriate joints and voluntary contractions.

(2) With the apparatus used no electrical activity could be recorded in *healthy limb muscles* which were completely relaxed Activity persists in certain respiratory and cervical muscles and is only abolished with difficulty in abdominal and facial muscles.

(3) Weddell, Feinstein and Pattle (1944) have made an analysis of muscle tone in relation to activity of the motor units.

(4) The electrical activity of denervated human muscle has been recorded Weddell *et al* first recorded repetitive sustained fibrillation action-potentials on the twelfth day after denervation of the erector spinae and on the eighteenth day in muscles of the forearm Warming the limb increases activity and cooling suppresses sustained fibrillation. The mean time of onset of fibrillation in proximal, intermediate and distal segments of the upper limb was 19 days, S E. $\pm$ 2 19·5 days, S.E. $\pm$ 2 36 and 26 days, S E. $\pm$ 2 5 respectively The data are not considered sufficient to permit analyses of the effects of the age of the patient the position of muscle in the limb splinting, and physiotherapy upon the time of onset of fibrillation—which is very variable

of peripheral nerve injury Since appropriate treatment and reliable prognosis are largely dependent upon correct diagnosis, any refinements in diagnostic methods merit attention. With a clinical examination which includes a sweating test and investigation of the electrical reactions it is usually possible to decide whether the lesion in a nerve trunk is complete or partial and whether it is degenerative or non-degenerative. However when the case is first presented for examination, it is not always possible to be certain whether a complete degenerative lesion is the result of a division or of a lesion in continuity of the nerve trunk. Two courses of action are open one is to explore the nerve without delay the other to watch the progress of the case. Experience has shown that certain types of closed injury may be treated conservatively but where there is an open wound or a compound fracture, exploration is at present the only certain method of assessing the state of the nerve short of waiting to see the progress of recovery Electromyography has nothing to offer in the solution of this problem but if it gives a more complete clinical picture and if it is capable of providing early and reliable evidence of the presence and extent of regeneration of damaged nerve fibres its place in routine clinical work is assured The findings in various types of injuries of peripheral nerves have already been described briefly but it is now necessary to consider them in relation to the problems of diagnosis and prognosis.

Early diagnosis is desirable for many reasons valuable time is saved in planning the appropriate course of treatment, and operations if they are necessary can be undertaken without undue delay there is no doubt, too that the patient's morale benefits from an early appraisal of his condition

Complete degenerative lesions A complete degenerative lesion cannot be diagnosed with certainty by electromyography for at least two weeks after injury and possibly not much before four weeks Fibrillation action potentials indicate the presence of denervated muscle fibres, but in limb muscles sustained fibrillation does not appear until about the eighteenth day The time of onset of fibrillation varies considerably in muscles of the upper limb The insertion type of fibrillation action potentials may appear as early as the sixth day and as late as the forty third The early electromyographic diagnosis of a degenerative lesion is still further complicated by the fact that the insertion type of motor unit action potential persists for varying periods after infliction of a complete degenerative lesion for example, as late as the twenty fourth day These insertion motor unit action-potentials are invariably present in cases of neurapraxia

The relative merits of electromyography and examination of the electrical reactions of muscle and nerve are illustrated in Fig 162, Case S 99 A boy aged fourteen years, cut the left wrist and there was immediate complete ulnar paralysis the nerve was subsequently found to be completely divided. On the second day after injury the electrical reactions were normal the muscles contracted when the nerve was stimulated below the level of the injury but no response was obtained proximally On the third day there was a rise in the threshold of response of the muscles to stimuli of 1/1000 second duration and a feeble contraction was obtained in abductor minimi digiti when a current of 9 milliamps was applied over the course of the ulnar nerve below the level of injury This current was abnormally high and the contraction might possibly have been due to a direct spread to the muscle. By the fourth day no response was obtained on percutaneous stimulation of the nerve. This finding suggested a complete degenerative lesion On the twelfth day the insertion type of fibrillation action potentials were found in abductor minimi digiti but spontaneous fibrillation was not

found until the twentieth day The reaction of degeneration was fully established in abductor minimi digiti by the seventeenth day In the fourth dorsal interosseus (Fig. 163) a feeble response to stimuli of 1/1000 second duration persisted, although the threshold was abnormally high This response might have indicated that a few of the fibres of the muscles were still innervated, but no motor unit action potentials could be recorded on attempted voluntary movement. These findings confirmed the clinical diagnosis of a complete degenerative lesion of the ulnar nerve which had been indicated as early as the fourth day by electrical reactions It is clear from the figures that repeated testing by both methods of investigation is desirable since a single reading may be misleading.

Partial degenerative lesions The diagnosis and treatment of a partial degenerative lesion may sometimes prove difficult and here electromyography may make a valuable contribution. It is a delicate method of detecting the presence of a few intact motor units and once the necessary time has elapsed it is equally delicate for detecting minor degrees of denervation. However it is a method of sampling which has a markedly limited range and therefore many readings may be necessary if a misleading impression of the case is to be avoided The delicacy of the method has been of particular use in the investigation of such conditions as Bell's palsy and paralysis associated with closed fractures of limbs, the finding of intact motor units having averted operation on numerous occasions However if facial paralysis has developed after mastoidectomy or if there is an open wound or compound fracture in a limb the finding of a few motor units cannot be taken as satisfactory proof of continuity of the greater part of the nerve or as a guarantee of useful functional recovery The decision to explore the nerve must be made on general surgical considerations.

The possibility of anomalous innervation should always be borne in mind, particularly when dealing with injuries of the median and ulnar nerves. The findings in a case with anomalous innervation might be identical with those of a partial injury even if the damaged nerve were completely severed. Fibrillation action-potentials and motor unit action potentials would both be found in muscles receiving a dual innervation. Electromyography gives no indication of the origin of the intact motor nerve fibres (Bowden 1946) Operations on the median or ulnar nerve have been delayed on account of the presence of motor unit action-potentials or even feeble voluntary contractions in muscles normally supplied by the damaged nerve. Electrical reactions of the muscles in such cases are characteristic of partial lesions Blocking the appropriate nerves by an intra or perineural injection of local anaesthetic would temporarily abolish the motor unit activity in response to voluntary effort on the part of the patient. However the anomaly can usually be detected more simply by percutaneous electrical stimulation of the appropriate nerve trunks, a procedure which should be carried out as a routine in injuries of the median or ulnar nerves (Bauwens, 1941a)

In partial lesions of the plexuses electromyography may give a more complete picture of the distribution of the damaged nerve fibres, and Weddell *et al* (1944) used it as an additional means of locating a root lesion, as for example in prolapse of an intervertebral disc but, as these authors point out, an accurate diagnosis had usually been made by an experienced clinician without the aid of electromyography The presence of a lower motor neurone lesion which had been superimposed upon an upper motor neurone lesion may be confirmed by electromyography but the experienced clinician is usually able to detect its presence without difficulty

A M D

NERVE CONDUCTION 3 M.A

? NERVE CONDUCTION 9 M.A

NERVE CONDUCTION NEGATIVE

FIBRIL IRRIT

FIBRILLATION 1 2 SPIKES

DURATION OF STIMULUS

1/1000 SEC

1/50 SEC

1 0 SEC

THRESHOLD STIMULUS IN MILLIAMPS

40 35 30 25 20 15 10 5 0

Control A M.D

5 0

5 10 15 20 25 30 35 40

OEDEMA

INJURY VISIBLE WASTING

TIME IN DAYS

FIG. 162. S.99—boy 14 years. Neurotmesis, left ulnar nerve.

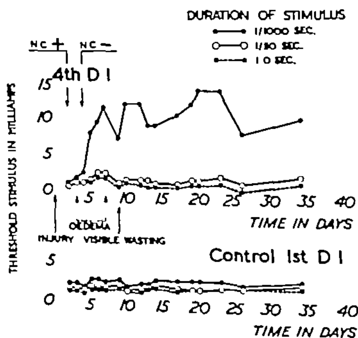


FIG 163 S 99—boy 14 years. Neurotmesis, left ulnar nerve.

The diagnosis of non-degenerative and mixed degenerative and non-degen lesions In cases of neurapraxia motor units of the insertion type are invariably and Weddell *et al* found there are usually a few motor unit potentials on voluntary effort, thus indicating physiological continuity o of the nerve fibres In such injuries electrical testing shows that nerve cond persists distal to the injury and the electrical reactions of the muscles are n However uncomplicated neurapraxia is rare in clinical practice, since e *myography usually reveals scattered fibrillation (Fig. 155 p 272)*

The diagnosis of myopathies It is commonly possible to distinguish b paralysis of neurogenic and myopathic origin by clinical examination a the progress of the case but occasionally diagnostic difficulties arise. hoped that electromyography would be of considerable value in such c stances. It was once thought that the finding of fibrillation action pot was pathognomonic of a degenerative lesion of the lower motor neurone were the case the distinction between neuropathies and myopathies wo simple. Electromyographic studies have yielded information abou myopathies but hopes of finding a reliable diagnostic test have not been fu for action-potentials which are indistinguishable from fibrillation action tials have been recorded in proven cases of myopathy (Weddell, Feinste Pattle 1944 Kugelberg, 1947 and 1949 Bowden and Gutmann, Carmichael personal communication)

Prognosis The prognosis of a nerve lesion is dependent, amongst other t upon the nature of the lesion in the nerve and upon the state of the end-o The contribution that can be made by electromyography to diagnosis ha indicated and we have seen that in a complete degenerative lesion none available methods of investigation can solve the problem of whether c there has been a breach of continuity of the nerve trunks It is still nec to be guided by general surgical considerations. In certain *closed* injuries, el myography has something to offer as an aid to prognosis. Provided anom innervation can be excluded, the finding of even a few motor unit a potentials in response to voluntary effort indicates the presence of some nerve fibres, and experience has shown that a certain degree of sponta recovery is to be expected It is therefore justifiable to treat such a case servatively and watch for signs of progressive re innervation The nee careful supervision of closed injuries in which the nerve is likely to be sub to repeated minor traumata has already been stressed Increasing sig spontaneous motor unit activity are probably unfavourable and may in the need for an exploratory operation

If recovery of function after suture or a lesion in continuity is delayed be the expected time electromyography may be of considerable assistance. of progressive re innervation of muscle afford the earliest evidence of n recovery in much the same way that a steady advance of Tinel s sign ind sensory regeneration For example Case B 63 (Fig. 161) gave rise to conside anxiety because of delayed recovery after suture of the radial nerve. How re-exploration was delayed on account of electromyographic evidenc progressive re-innervation and events justified this conservative attitude there is more evidence that Bauwens method of assessment has fulfille intention electromyographic signs of progressive re innervation should n given more weight than is accorded to a steadily advancing Tinel s sign (Na and Rennie 1946 Henderson 1948 Napier 1949)

The state of the end-organs is important, and the highest degree of re innervation is of no avail if muscles have undergone irreversible change. Weddell *et al* (1944) had the impression that vigorous fibrillation indicated a satisfactory state of the muscle fibres but for several reasons this view does not seem to be wholly justified The volume of tissue from which recordings are obtained with a needle electrode is small and the process of atrophy is most uneven even within a single denervated muscle Fibrillation is suppressed or diminished by cooling the limb and there also is an apparent diminution in fibrillation in the early stages of recovery In such cases the threshold to electrical stimulation may rise, but a good response is obtained with a strong current. In advanced stages of denervation and in muscles that have undergone severe ischaemic changes, the responses to electrical stimuli are poor or absent even with high currents Thus isolated electromyographic readings may be misleading, or equivocal A more comprehensive and accurate picture of the state of the muscle is obtained by considering the degree of wasting of the limb the consistency of the muscles on palpation and the results of percutaneous electrical stimulation and electromyography all together Even these may be inadequate and in a few cases it is necessary to resort to examination of biopsy material (Bowden and Gutmann, 1945)

6 Conclusions

(1) Electromyography is a delicate means of detecting minor degrees of denervation of muscle, and of detecting the presence of a few intact motor units in an otherwise denervated muscle

(2) The electrical reactions of muscles and stimulation of the affected nerves below the level of injury permit the diagnosis of a degenerative lesion of the nerve within about four days after injury more particularly if the technique is standardized and the effective stimuli can be measured These methods are superior to electromyography in making a diagnosis within the first four weeks of injury but they are considerably more time-consuming.

(3) There are no means of detecting the presence of anomalous innervation by electromyography unless the appropriate nerves are blocked with a local anaesthetic, but percutaneous electrical stimulation of appropriate nerve trunks usually reveals an anomaly

(4) Isolated electromyographic recordings and isolated tests of electrical reactions may be misleading and systematic repeated observations are desirable preferably using the contralateral healthy limb for control readings of electrical reactions.

(5) The earliest signs of recovery of motor function after injury to the nerve are obtained by electromyography

(6) Electromyography is clearly a useful means of investigation for the research worker and if taken in consideration with a full clinical examination it has its place in the management of peripheral nerve injuries.

VII

FACTORS INFLUENCING FUNCTIONAL RECOVERY

by Ruth E. M. Bowden

1 General Introduction

In assessing the results of treatment of peripheral nerve injuries it is not enough to grade the degree of restoration of motor and sensory function. Success of recovery must be judged in relation to the patient's ability to resume the enjoyment of a full and useful life. There is a real distinction between what may be termed academic recovery and functional recovery. Many factors influence the final result; some are operative from the moment of injury and others arise subsequently. As Young (1942) has stressed in a review of "The Functional Repair of Nervous Tissue" it is essential to realize the distinction between outgrowth of nerve fibres and the restoration of function. Many processes are involved in achieving functional recovery; there must be the downgrowth of an adequate number of appropriate nerve fibres, the formation of functional unions of the axons with the end-organs, the reversal of atrophic changes in the end organs and the maturation of the nerve fibres to such a state that they can conduct nerve impulses at the appropriate speeds and frequencies. Thus recovery to a normal state must depend upon a restoration of the mechanism of transmission and integration of impulses in the whole nervous pathway. We do not know the extent to which the central connexions are affected by the degeneration and regeneration of their peripheral segments, but clearly this factor cannot be ignored and demands further investigation.

Furthermore it is necessary to consider the effect of injuries of bones, joints and soft tissues. These associated injuries influence recovery from the nerve lesion and may of themselves impair the usefulness of a limb. Treatment must also be considered, for during the period of recovery after a nerve lesion there are methods of minimizing disability by judicious use of appliances. Lastly, but by no means least, it is desirable to know the extent to which the patient himself and the conditions of his life and employment can contribute to the recovery of function and to the reduction of the disability to a minimum.

One of the fundamental factors influencing functional recovery is the nature of the lesion in the nerve. In Chapter 3 it was shown that this will determine the number and appropriateness of axons that reach the periphery. The effects of delay in operative repair, the method adopted and the level of the lesion upon re-innervation of the distal stump, are all significant; the analysis of results in Chapter VIII also gives indirect evidence about these points. In this chapter attention will therefore be confined to a study of the effects on nerve regeneration of changes in the periphery and to the role of various forms of treatment that have been designed to counteract the effects of injury and lastly an attempt will be made to assess the influence of certain psychological factors on functional recovery.

2 Changes in Voluntary Muscle

A INTRODUCTION

The state of knowledge of the reaction of voluntary muscle to denervation was reviewed by Tower (1939), who had previously determined the part played by the various components of the peripheral nervous system in the production

of this response in the cat (1931a, b 1932 1935a 1937) She also made a systematic study of the histological changes found in the cat s interosseous muscles during the course of one year s denervation She distinguished three phases called progressive atrophy acute sporadic degeneration and fibrotic de-differentiation, and it appeared that in the course of time the contractile elements of muscle underwent irreversible changes which ultimately precluded the possibility of functional recovery Although systematic studies of the changes during denervation in man were lacking, there was evidence that the process resembled that found in experimental animals. The phenomena of re-innervation had been investigated but only in animals, by Tello (1907) and Boeke (1916) and these studies were limited to muscles re-innervated after short periods of denervation (one to two months)

For a better understanding of the treatment of peripheral nerve injuries inflicted in modern warfare, it was desirable to know

(1) The time-course of changes due to denervation of voluntary muscle in man
(2) The influence of the type of injury to a main nerve trunk upon the subsequent pattern of re innervation of muscle.
(3) The effects of different degrees of atrophy in the muscles themselves upon the process of re-innervation.
(4) The effect upon functional recovery of the changes in muscle due to vascular damage or prolonged exposure to cold and immersion in water

These problems were investigated in Oxford, Gogarburn and Edinburgh and the results of clinical and experimental observations will be reported briefly

B MATERIAL

The material for this study of denervation and re innervation consisted of biopsies of muscle obtained at operation in 86 cases of peripheral nerve injury admitted to the Oxford Centre. As experience was gained, these specimens were found useful as aids to diagnosis and prognosis, and sometimes in the planning of treatment. The periods of denervation before biopsy ranged from 42 days to 30 years. As details of technique and histological examination have been fully reported elsewhere (Bowden and Gutmann, 1944) only a summary will be given here

Attention will be drawn briefly to those histological features which become modified during denervation and re innervation.*

C CHANGES DURING DENERVATION

In normal muscle the fibres are held together by connective tissue in compact bundles or fasciculi These fibres lie parallel to each other (Fig. 164) and are characterized by well marked cross-striations. By using a modification of Bielschowsky s silver stain, deeply staining granules of uniform size were found arranged in an orderly manner on the borders of the dark bands (Fig. 165) Similar structures had been observed in the wing muscles of insects by Koelliker (1857) and Holmgren (1910) but they had not been reported previously in human muscle. Unless muscle fibres are teased, it is usually difficult to demonstrate the constituent fibrils. The muscle nuclei lie at the periphery of the fibres immediately under the surface membrane The structure of the motor end plates does not differ greatly from that observed in the rabbit by Gutmann and Young

* The photomicrographs are the work of Dr E. Gutmann, who also made the histological preparations. All preparations are of human muscle. Unless otherwise stated, the material has been stained with a modification of Bielschowsky s technique



FIG. 164 Normal muscle fibres arranged in compact parallel bundles. The muscle nuclei are on the periphery of the fibres. The normal pattern of innervation is clearly shown. The terminal branches of myelinated nerve fibres which are innervating the end-plates lie near the nerve trunks. An end-plate is seen in lateral view on the left.

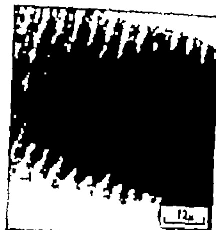


FIG. 165 Regularly spaced granules are seen on the borders of the darkly staining bands in a normal muscle fibre.



FIG. 166. Lateral view of a normal end-plate with tapering and bulbous terminations on the axon.

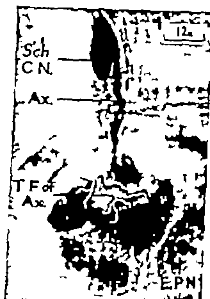


FIG 167 A normal end-plate with the darkly staining Schwann cell nucleus (Sch. C.N) close to the entering nerve fibre (Ax) and the plumper lightly stained inner' or 'true end-plate nuclei. (E P.N.). Note the terminal filaments (retouched) of the nerve fibre (T.F of Ax.)



FIG 168 A normal end-plate. The terminal axon is thickly myelinated down to the point of entry

(1944) These contain three types of nuclei, the true or inner end-plate nuclei the outer end plate nuclei and the Schwann-cell nuclei The true or inner end-plate nuclei lie within the sarcoplasm and stain more darkly with silver than the muscle nuclei they have one, sometimes two heavily stained nucleoli. On the average there are about eight of these nuclei in rosette formation in each end-plate. The outer end plate nuclei which are irregular in shape, are contained in fibrocytes, whilst the oval Schwann-cell nuclei are seen lying close to the entering nerve fibre (Figs. 166 and 167) Normally the nerve fibres can be followed in the

individual Schwann tubes leading to the motor end plates The axons are thickly myelinated down to the point of entry into the end plates and terminal branching occurs close to the end plates for which they are destined and within which they break up into filaments (Figs 167 and 168) The richness of the normal blood supply to voluntary muscle is indicated by the elaborate network of capillaries that anastomose freely (Fig. 169)

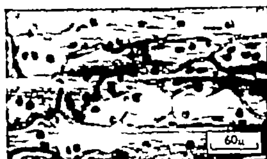


Fig. 169 The pattern of capillaries with numerous anastomoses in a normal muscle.



Fig 170 69 days after denervation. The pattern of the Schwann tubes is still clearly outlined. Note the wavy arrangement of muscle fibres.

Even in muscle denervated for as short a period as six weeks, there are conspicuous changes in the arrangement of the muscle fibres. The essential change is a shrinkage in the diameter of individual fibres. The compact arrangement is lost, spaces are found between the fibres which no longer appear straight but wavy in outline when seen in longitudinal section (Fig. 170) Not only is the disposition of the fibres disturbed but there are striking intracellular changes. Spaces appear between the constituent fibrils which are then more easily identified (Fig. 171) These extra and intra-cellular spaces have been attributed to intra muscular oedema in the early stages of denervation and to shrinkage of the fibres in the later stages (Tower 1939) There is an apparent increase in the number of the nuclei which, normally subsarcolemmal come to be arranged in rows or clumps towards the centre of the fibres (Fig. 172) Neither in previous work nor in this investigation have mitotic figures been reported The decrease in volume of the muscle fibres would result in there being more nuclei per volume of tissue and this might be sufficient to explain the apparent increase in the number

Shrinkage of muscle fibres, though difficult to detect in early cases, is progressive, but not equal in all fibres. Not only are there variations in the size of fibres in different individuals and in different muscles, but even in a single specimen there is a striking lack of uniformity There is also variation in the staining of the cross-striations which may become less or occasionally even more evident than normal When these bands are no longer easily seen in stained preparations, bi refringence can sometimes be detected by means of polarized light, even as long as 23 years after denervation Granules on the dark bands become more conspicuous and irregular in size and arrangement. In association with the shrinkage of the contractile elements there is a progressive increase of connective tissue, first in the perivascular regions (Fig. 173) and then between fasciculi and individual fibres (Fig. 174) During the first two or three years after denervation there is no obvious sign of hyaline, granular or fatty degeneration within the fibres, although it is probable that submicroscopical degenerative changes are



FIG. 164 Normal muscle fibres arranged in compact parallel bundles. The muscle nuclei are on the periphery of the fibres. The normal pattern of innervation is clearly shown The terminal branches of myelinated nerve fibres which are innervating the end-plates lie near the nerve trunks. An end-plate is seen in lateral view on the left

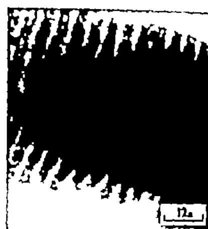


FIG 165 Regularly spaced granules are seen on the borders of the darkly staining bands in a normal muscle fibre.

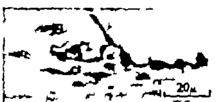


FIG 166. Lateral view of a normal end-plate with tapering and bulbous terminations on the axon.



FIG 168. A normal end-plate. The terminal axon is thickly myelinated down to the point of entry

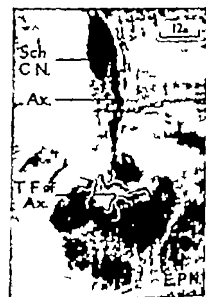


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FIG. 169 The pattern of capillaries with numerous anastomoses in a normal muscle.



FIG 170 69 days after denervation The pattern of the Schwann tubes is still clearly outlined. Note the wavy arrangement of muscle fibres.

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FIG. 171 A muscle fibre 69 days after denervation. The sarcoplasm of the end-plate is still conspicuous and the individual Schwann tube can be followed to the old end-plate. Note the loosened arrangement of the fibrils inside the muscle fibres.



FIG. 172. 78 days after denervation, showing the nuclei of the muscle lying together in short rows or clumps, towards the centre of the fibre.

FIG. 173 69 days after denervation, showing the increase of connective tissue and fat apparently beginning round the vessels.



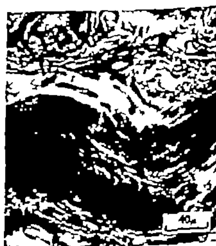


FIG. 174 3 years after denervation, showing the unequal shrinkage of the muscle fibres, and increase in fat and connective tissue.

taking place. These lead ultimately to the disruption and fragmentation of the muscle Some of the more advanced changes can be seen in Figs. 175 to 187 which illustrate various stages of degradation of the tissue. Gradually as the muscle fibres shrink, the whole muscle is replaced by connective tissue and fat, in which a few fragments of muscle fibre may be identified (Figs 177 181 and 186) Fig. 187 shows a sample of tissue indistinguishable from tendon but there was no evidence of a direct transformation of muscle fibres into connective tissue such as that described by Tower as fibrotic de-differentiation The process appears to be *one of replacement only*

Along with changes in muscle fibres and their nuclei there are alterations in the intramuscular neural elements. The nerve fibres undergo Wallerian degeneration and the empty Schwann tubes can be traced down to the end plates (Figs. 170 and 171). The latter can be identified with reasonable certainty up to about nine months after denervation, but it becomes increasingly difficult to see them where there is severe shrinkage of muscle fibres. The general arrangement of intramuscular nerve trunks can be followed (Figs. 188 and 189) but the terminal Schwann tubes and smaller nerve trunks become less easily identified as they become embedded within connective tissue and invaded by histiocytes (Figs. 188 and 190) *In the most advanced stages they can no longer be found.*

The earliest change observed in the intramuscular blood vessels is a thickening of the endothelium of the capillaries, while the endothelium and media of the larger vessels also undergo progressive proliferation (Figs 191 and 192) The capillary network becomes distorted and eventually it is impossible to identify these small vessels It could not be determined whether the atrophy of muscle was the result of diminished blood supply associated with gradual obliteration of the smaller vessels, or whether this altered vascular pattern reflected the decreasing functional demands of the muscle

Although there was insufficient material to permit determination of the influence of age, overstretching, sepsis and various forms of treatment on the rate of atrophy it is of interest that in three children aged 2, 11 and 12 years the muscle showed changes much in advance of those found in adults whose muscles had been denervated for comparable periods *This is in keeping with* the experimental observations of Hines, Thomson and Lazere (1942) who showed that in the rat the rate of wasting decreased with the age of the animal

Shrinkage of muscle fibres although sometimes difficult to detect in the first three months, is probably present even in the earliest stages of denervation However the variations in the degree of atrophy in different individuals and muscles show that the time of denervation is not the only factor which determines the degree of wasting. Although in this study gross disruptive changes of the muscle fibres were not observed before about three years it is probable that serious alterations occur before this time. The general conclusion was that some useful recovery of function may be expected *provided the muscles are adequately re-innervated* within about a year after injury to the nerve The prognosis deteriorates with longer periods of denervation and the prospects become extremely poor after about three years.

D RE INNERVATION OF VOLUNTARY MUSCLE
EXPERIMENTAL OBSERVATIONS

Gutmann and Young (1944) *studied* the normal pattern of innervation of muscle in the rabbit, and the re innervation of muscle after different types of injury to the nerve and varying periods of denervation The motor end plates

Illustrations referred to in C Changes during Denervation



Fig 175 26 years after denervation. Note the round and oval fragments of muscle fibres surrounded by nuclei lying embedded within the connective tissue. (Haematoxylin-eosin.)



Fig. 176. 14 years after denervation An atrophic muscle fibre filled with clumps of nuclei.

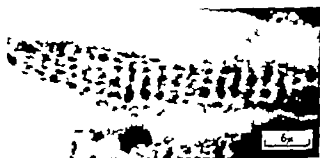


Fig. 177 20 years after denervation. Highly atrophic muscle fibre with granules of unequal size, in orderly alignment at the level of the Q bands.



FIGS. 178 and 179 20 years after denervation. Highly atrophic muscle fibres with irregularly distributed granules.

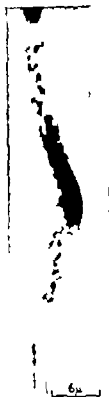


FIG 180 25 years after denervation An attenuated remnant of a muscle fibre with a single row of granules arranged longitudinally at one end.

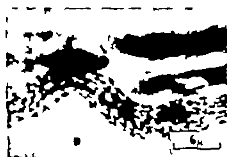


FIG. 181 25 years after denervation. Highly atrophic muscle fibres with irregularly distributed granules.

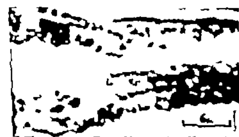


FIG. 182. 25 years after denervation, showing two highly atrophic muscle fibres containing irregularly distributed granules of varying size.



FIG 183 25 years after denervation. Last remnants of atrophic muscle fibres resembling fibroblasts.



Fig. 184 26 years after denervation. A muscle fibre with the sarcoplasm retracted from the sarcolemma. (Haematoxylin-eosin.)

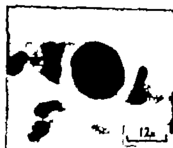


Fig. 185 26 years after denervation. A droplet of hyaline material within an atrophic muscle fibre. (Haematoxylin-eosin.)



Fig. 186. 3 years after denervation, showing part of the muscle replaced by fat and connective tissue. (Sudan-haematoxylin.)



Fig. 187 25 years after denervation, showing the elongated connective tissue cells resembling tendon.



Fig. 188 250 days after denervation. The pattern of the nerve trunks and Schwann tubes is still unaltered and clearly recognizable.



FIG. 189 250 days after denervation. An empty intramuscular nerve trunk with the individual Schwann tubes clearly outlined.



FIG 190 5 years after denervation. Large intramuscular nerve trunk embedded in connective tissue and fat.



FIG 191 145 days after denervation, showing collections of leucocytes round the vessels.



FIG 192. 145 days after denervation A small intramuscular artery with narrowed lumen and thickened media.

may remain intact for a year or longer after denervation. The outer fibrocytes increase in number but there is *no alteration in the number of true end-plate* nuclei When a nerve was crushed close to the muscle, one fibre returned down each Schwann tube leading to an end plate and branched freely in contact with its sarcoplasm. The number of terminal filaments within the end plates returns to normal after about 70 days, although in many plates they appear somewhat abnormal in shape. The delay between the entry of fibres into the muscle and the onset of reflex contractions was 11 days.

If the nerve is crushed some distance from the muscle, thereby imposing a longer period of denervation part of the returning axoplasm often leaves the original Schwann tube and forms an ultra terminal fibre Some end plates were then not re-innervated and new plates were formed where the ultra terminal fibres touch the sarcoplasm. The number of endings in the individual plates reached normal in about 100 days. The interval between the return of axons to the muscle and the onset of reflex activity was longer than when the nerve was *interrupted near the muscle, namely 22 days.*

After severance and immediate suture of a nerve the tendency to formation of ultra terminal fibres was increased, and a considerable number of end-plates were not re-innervated Many small fibres which enter the muscle after its nerve has been sutured are presumed to be autonomic or sensory nerve fibres. They do not enter end plates but form elaborate networks along the muscle fibres. These plexuses are still visible one year after suture. When a large and a small fibre approach a plate, the larger alone enters into it. The number of nerve endings in an end plate is subnormal even after one year The delay between entry of fibres and onset of reflex activity was 25 days when severance and suture were close to the muscle, but this delay increased to 55 days if suture of the nerve at the same low level was delayed for nine months.

With increasing periods of denervation the proportion of old end-plates which become re innervated is progressively reduced. In re-innervation of *muscles in advanced stages of atrophy most of the nerve fibres escape from the* original terminal nerve bundles and Schwann tubes, and run along between muscle fibres or across them. New end plates form if these nerve fibres ultimately make contact with the sarcoplasm. Thus the effectiveness of re-innervation is prejudiced by prolonged atrophy The authors consider that at least three factors contributed to this namely

(*a*) The increasing difficulty and slowness with which new end-plates are formed.

(*b*) The abnormality of the pattern of re-innervation, and the consequent *increasing likelihood of wrong connexions.*

(*c*) The fact that many muscle fibres are never re innervated at all

Gutmann (1945) showed that re-innervation by sensory fibres could *not* restore function in or prevent atrophy of a denervated muscle.

E RE INNERVATION OF VOLUNTARY MUSCLE IN MAN

By study of the series of biopsy specimens mentioned above, it has been possible to follow the course of re-innervation of human muscle.

The findings were essentially the same as those observed by Gutmann and Young (*1944*) *and are illustrated by photomicrographs. The diagnosis was based* on the history the clinical examination, the appearance of the nerve (if this was exposed at operation) and the ultimate progress of the case. In each case an

attempt was made to determine the time at which nerve fibres might have reached the muscle under examination the methods used have been described (Bowden and Gutmann, 1944) The difference between the number of days required for nerve fibres to reach a given muscle and the number of days that had elapsed between injury or repair of the nerve and the muscle biopsy was termed the *hypothetical period of re innervation* This term therefore defines the time during which nerve fibres would have been present in the muscle, had regeneration taken place at the expected time.

Although this was found to be a useful working hypothesis it is unjustifiable to claim that it has any great degree of precision for the rate of advance of axon tips and the length of the initial delay used in the method are both based on assumptions, and several other variable factors have been taken into account. For instance, the exact distance between the upper limit of the degenerative changes in the nerve and the point of entry of the nerve into the muscle cannot be measured precisely being dependent upon the extent of the retrograde degeneration of the nerve fibres and upon anatomical variation in the points of innervation of the muscles (Sunderland, 1946 1947) Moreover the distribution of the nerve fibres within the muscles is not yet fully known. The time taken by the axons to cross the site of injury is influenced by the density of the scar tissue and the rate of outgrowth of the axon tips is probably not constant in man The calculation is at best only an approximation. (See Chapter I Part II for full discussion.)

The method of calculation and the practical application of the *hypothetical period of re-innervation* are best illustrated by an example

Case H 47 This man had an injury of the posterior interosseous nerve as a result of a gunshot wound of the forearm. From the history and clinical findings, it was not possible to exclude division of the nerve and it was therefore explored 47 days after injury The nerve was found to be in continuity and there was a soft intraneural swelling 1 cm long, extending from 6 cm. to 7 cm. below the lateral epicondyle of the humerus.

The distance between the epicondyle and the point of entry of the nerve to abductor pollicis longus is 11 cm. (Feinstein and Highet). Therefore the approximate distance between the lesion and the point of entry of the nerve to the muscle was 5 cm. (11 *cm.* – 6 *cm.*) See p. 19

Assumed rate of advance of axon tips	= 3 mm. per day
Therefore, time taken to grow 5 cm.	= about 17 days
Assumed delay at the scar	= 20 days

Hypothetical period of re innervation is (47–(20+17)) = 10 days.

The first nerve fibres that would have been likely to reach the muscle probably arrived about 10 days before the operation at which the biopsy was taken Therefore one could not expect to find more than a few thin axons innervating the end-plates and the intramuscular nerve trunks. This was found to be the case (Fig. 193). Since axons had reached the muscle within the expected time, a diagnosis of axonotmesis was made on the grounds of the biopsy and the nerve was left to recover without further interference. This diagnosis was ultimately confirmed by a recovery that was clinically indistinguishable from normal.

(i) *Re-innervation after Axonotmesis*

After an axonotmesis it was noted that the number and degree of maturation of nerve fibres in a muscle corresponded well with the expectation based on the principles set out above Numerous nerve fibres of apparently equal degrees of maturation were found in the nerve trunks. Fig. 194 shows the first thin regenerating fibres found in a muscle 78 days after injury the hypothetical period of re innervation in this case was only eight days, This agrees with the presence of small fibres in the nerve trunk An empty end plate in a more distal muscle of the same case is shown in Fig. 195 On the basis of the calculation re-innervation was not expected in this biopsy specimen for at least another eight days. This patient vounteered in the interests of the investigation, to have a second biopsy

may remain intact for a year or longer after denervation The outer fibroc increase in number but there is no alteration in the number of true end p nuclei When a nerve was crushed close to the muscle one fibre returned dc each Schwann tube leading to an end plate and branched freely in contact v its sarcoplasm The number of terminal filaments within the end-plates retu to normal after about 70 days, although in many plates they appear somew abnormal in shape The delay between the entry of fibres into the muscle a the onset of reflex contractions was 11 days

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which was made 119 days after the first The hypothetical period of re-innervation of the muscles examined was then 111 and 104 days respectively By this time there were numerous nerve fibres in a more advanced stage of maturation (Fig. 196 cf Fig. 194) In case H 47 (Fig 193) there was a hypothetical period of re-innervation of ten days at the time of the biopsy and numerous small nerve fibres were found It was of interest to note that the first signs of recovery of voluntary power were not detected until 50 days later

The early stages of re innervation of an end plate are shown in Figure 198 from a specimen of muscle with an hypothetical period of re innervation of 44 days. An intramuscular nerve trunk from the same case is shown in Figure 197 In the later stages a high degree of maturation of nerve fibres was noted after axonotmesis (Fig 199) although the terminations of the axons in the end-plates were abnormal in shape (Fig. 200 cf Fig 167) Both Figs. 199 and 200 show the state of affairs ten and a half months after injury in a muscle which had probably contained regenerated nerve fibres for at least nine months

Re innervation after a successful suture There was no justifiable opportunity for taking biopsies from any case in this category The experimental findings of Gutmann and Young (1944) are reported on page 308

(ii) *Re-innervation after Unsuccessful Suture*

Poor recovery after repair of a nerve may be due to one or more factors, working singly or in combination Although a detailed discussion is out of place, two examples will be considered Firstly at the site of suture, the disposition and density of the scar tissue in the proximal and distal stumps will determine the number and destination of the axons that ultimately reach the end organs Secondly the state of the end-organ itself will affect not only the maturation of the regenerated nerve fibres which reach it (Weiss, Edds and Cavanaugh 1945 Sanders and Young, 1946 Aitken Sharman and Young, 1947) but will also profoundly influence the restoration of function.

Where the nerve fibres reaching a muscle are inadequate in number or kind many muscle fibres are never re innervated Signs of this were found in biopsies of muscle taken from cases which either failed to recover or made poor recoveries. The progressive atrophic changes within the muscle increase the difficulties of re innervation and nerve fibres escape from the terminal fascicles and Schwann tubes which have been invaded by histiocytes The axons run for long distances along or across the muscle fibres (Fig. 201) New end plates were sometimes formed but many axons failed to make satisfactory contact with the muscle and they ended in connective tissue, some of them showing terminal end knobs (Fig. 202) On the other hand regeneration of the nerve might be satisfactory but the muscle had undergone irreversible alterations in structure (Fig. 203) This specimen was taken from a boy who had suffered a compound fracture of the humerus, later complicated by gross infection and accidental division of the radial nerve. About seven years after injury the radial nerve was repaired In spite of the large number of thick myelinated nerve fibres which reached the muscles, the atrophic changes had proceeded too far to allow restoration of function

(iii) *Re-innervation after Unaided Union or Traction Injury*

Although at first sight it might seem unwise to group these two types of injury together since their aetiology and pathology are so different, there is some justification for doing so for in both the damage to the nerve prevents



FIG 193 Case H 47 47 days after axonotmesis Nerve trunk innervated with only a few thin nerve fibres corresponding to early reinnervation after axonotmesis. (Hypothetical period of re-innervation 10 days.)



FIG 195 Case B.59 Empty end-plate in a slightly atrophic muscle.



FIG 194 Case B 59 Nerve trunk containing only a few thin fibres, corresponding with early re-innervation after axonotmesis. (Hypothetical period of re-innervation 8 days.)



FIG 196. Case B.59 197 days after axonotmesis. Nerve trunk now re-innervated with more numerous and thicker nerve fibres. (Hypothetical period of re-innervation 104 days.)

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FIG. 197 Case G 45 178 days after axonotmesis, showing early regeneration in the nerve trunk, corresponding with re-innervation after axonotmesis. (Period of re-innervation 44 days.)



FIG. 198 Case G 45. Showing re-innervation of an end-plate after axonotmesis. (Hypothetical period of re-innervation 44 days.)



FIG. 199 Case C.57 323 days after axonotmesis, showing normal degree of re innervation which can be achieved after axonotmesis.



FIG. 200 Case 57 323 days after axonotmesis, showing high degree of recovery of diameters of nerve and muscle fibres after axonotmesis. A thick nerve fibre is seen innervating an end-plate.



FIG 201 Case R 41 608 days after injury, 408 days after suture. The pattern of delayed re-innervation in a muscle. There is considerable atrophy of the muscle and the nerve fibres run for long distances along and across the muscle fibres. (Hypothetical period of re-innervation 298 days.)

adequate re-innervation. The histological findings in the muscles are therefore similar the intramuscular nerve trunks contain a number of empty Schwann tubes whilst the nerve fibres within them are remarkably variable in their degree of maturation However the similarity between the two groups ends when the prospects of early operative intervention are considered In favourable circumstances the end results of suture are superior to those of unaided union thus resection of the lesion and suture improve the prognosis (see discussion on Case B 52, Bowden and Gutmann 1945) In severe traction injuries the prognosis is invariably bad since repair of the extensive lesion is technically impossible.

(a) *Unaided union* The conspicuous lack of uniformity of innervation is shown in Figs. 204 and 205 These preparations were made from a biopsy specimen taken 335 days after an incomplete division of the median nerve in the arm Union of the severed portions of the nerve had been unaided If regeneration of the nerve fibres had occurred with the minimum delay at the site of the injury the axons should have been in the muscle for about 245 days. Since they were so immature it was deduced that there had been delay in the downgrowth of the nerve fibres. Some indeed had evidently been unable to reach the distal stump at all, since there were many empty Schwann tubes The inequality in maturation might have been due to the fact that some axons had failed to make connexions with suitable end-organs, or that they had encountered differing degrees of obstruction whilst penetrating the scar at the site of injury Some of the axons may have been autonomic fibres or fine cutaneous fibres

(b) *Traction injury* Case G 12 had sustained a severe traction injury which damaged all roots of the brachial plexus. A biopsy of muscle taken 600 days after the injury showed evidence of delayed and inadequate re-innervation (Fig. 206 p 317) From the calculation the nerve fibres might have been in the muscle for 483 days. Had re-innervation by motor nerve fibres taken place at this time the axons would have been in a more advanced state of maturation These thin nerve fibres indicated that re innervation had either been delayed or inappropriate and was functionally insignificant. The gross wasting of the muscle and absence of percutaneous electrical excitability suggest that this specimen was representative of the whole.

(iv) *Summary of Changes Found in Denervation of Voluntary Muscle in Man*

In denervation the salient features are

Muscle Fibres

(1) Conspicuous alteration in the arrangement of muscle fibres and their nuclei even in the early stages (e.g. six weeks after denervation)
(2) Progressive but unequal shrinkage of muscle fibres.
(3) Progressive but unequal fading of cross-striation of muscle fibres evidence of cross-striation may still be found 23 years after denervation
(4) Disruption of muscle fibres first seen about three years after denervation

Connective Tissue and Fat

(1) Increase of connective tissue and fat is progressive, and becomes apparent in the perivascular regions after about three months
(2) Invasion of terminal Schwann tubes and smaller nerve trunks by connective tissue is recognizable within about a year after denervation.
(3) There is gradual replacement of muscle by fibrous tissue and fat in the later stages of denervation



Fig 202. Case R 41 Nerve fibre running along muscle fibre and ending in a large bulb within the connective tissue. 608 days after injury 408 days after suture. (Hypothetical period of re-innervation 298 days.)



Fig 203 Case Q.2, showing a satisfactory degree of re-innervation in the intramuscular nerve trunks. No recovery was possible owing to the extreme degree of muscle atrophy Approximately 9 years after injury and 693 days after suture. (Hypothetical period of re-innervation 610 days.)

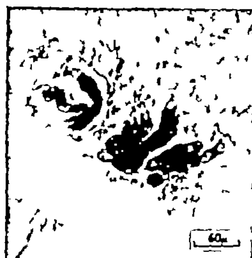


Fig 204 Case B.52, 335 days after injury showing the varying degree of re-innervation after an unaided union or traction injury Most of the nerve trunks are still empty others contain a few thin nerve fibres suggesting delayed re-innervation. (Hypothetical period of re-innervation 245 days.)



Fig. 205. Case B.52. (Cf. Fig. 206) showing a nerve trunk innervated with numerous rather thick nerve fibres. (Hypothetical period of re-innervation 245 days.)

Nerve Trunks and End plates

(1) The supporting tissue of the nerve trunks and the individual Schwann tubes can be identified after Wallerian degeneration is complete.

(2) Individual Schwann tubes can be traced down to empty end plates for about a year after denervation

(3) The nuclei of the end plates become altered but can be identified for at least nine to twelve months after denervation.

(4) There is progressive invasion of the terminal Schwann tubes and smaller nerve trunks by fibrous tissue.

(5) In the later stages (after about three years) only the larger nerve trunks can be identified with certainty

Blood Vessels

(1) Thickening of the endothelium of the capillaries and hypertrophy of the endothelium and media of the larger vessels was visible in the earliest specimens of the series taken six weeks after denervation These changes are seen more clearly in later cases

(2) In the later stages capillaries and smaller arterioles and venules can no longer be identified in some areas, and the lumina of larger vessels are almost obliterated.

(v) *Summary of Findings after Re-innervation of Voluntary Muscle in Man and in Rabbit*

(1) The nature of the lesion in the main nerve trunk determines the number and appropriateness of the nerve fibres reaching the muscle. It influences the degree of maturation of the axons The appearances of the intra muscular nerve trunks after re-innervation are therefore characteristic of different types of lesion.

(2) Changes in the muscle due to prolonged denervation lead to increasing difficulties in forming functional re-connexion between nerve and muscle fibres.

F CHANGES IN VOLUNTARY MUSCLE AFTER COMBINED PERIPHERAL NERVE AND VASCULAR LESIONS

Recovery of useful motor function after injury to a peripheral nerve can only be achieved if the state of the affected muscles is satisfactory where in addition there is gross damage to blood vessels the muscle is doubly threatened In this section attention will be confined to a review of the effect on muscle of partial or complete deprivation of blood supply The nature of the injuries inflicted upon main trunks in such cases is considered fully in Chapter V

The cases in which ischaemic muscle damage is encountered may be divided into four categories

(1) Open wounds with damage to main vessels or muscular branches

(2) Closed injuries of the limbs with damage to vessels

(3) Acute embolic catastrophies.

(4) More gradual ischaemia due to the slow formation of thrombi or to the accumulation of fluid or swelling of muscle within a rigidly bounded space such as the anterior tibial compartment

Ischaemic lesions in muscle have been attributed to

(a) Arterial occlusion (Volkmann, 1872 and 1893 Griffiths 1940 Barnes and Trueta 1942)

(b) Arterial spasm (Leriche 1935 Cohen 1941 1944)
(c) *Venous obstruction* (Brooks, 1922 Brooks and Martin 1923 Jon 1928 Middleton, 1930 Brooks, Johnson and Kirtley 1934)
(d) External pressure alone (Jepson, 1926 Lewis, 1936)
(e) External pressure in association with ligation of veins (Jepson, 1926)
(f) Capillary paralysis (Leveuf 1937)
(g) Peripheral nerve injuries (Putti, 1938)

Clinical and experimental evidence has been put forward in support of ea theory Leveuf (1938) and Griffiths (1940) have reviewed the subject fully a added their own clinical observations. Both have drawn attention to the f that conditions of different aetiology and pathology have been grouped togetl on the grounds that they produce contractures in voluntary muscle Indeed t strikingly different types of lesion have been reported, one in which there massive necrosis of contractile tissue and the other which is characterized dense intramuscular fibrosis.

In recent years microscopic and macroscopic study of muscle has shed mo light on these problems of aetiology on the possibility of functional restorati and on the special liability of certain muscle groups to ischaemia. Since classifi *tion of these lesions of muscle cannot be made satisfactorily on the basis* clinical signs, a histological classification may perhaps serve to distinguish o condition from another

(i) *Histological Classification of Lesions*

The appearances due to vascular damage in muscle are well known and ha been reported by many observers However a brief summary of the findings relevant, and is illustrated by photomicrographs made during treatment sixteen cases at the Oxford Centre.*

Three types of lesion are distinguishable histologically In the first, there massive necrosis of muscle fibres and the necrotic areas are surrounded by sharply defined zone of fibrous tissue. In the second there is dense interstiti fibrosis. The third group shows elements of the two previous types in that the *are scattered foci of necrosis together with interstitial fibrosis.*

(a) *Massive necrosis*

In five cases in which biopsy was performed the intervals between injury ar biopsy ranged from 40 to 800 days. The muscles were hard and friable to tou and there were patches of yellow green necrotic tissue Where the muscle fibr could be identified they were arranged in straight lines and were either norm in diameter or swollen There was no evidence of fibrillar structure within tl muscle fibres which showed considerable variation in staining reaction even i a single section (Fig. 207) No nuclei were seen in the longstanding cases, but i the more recent ones there were a few small nuclei of abnormal appearance an reaction to staining. Where present, cross striation was unusually clear althoug again there was no uniformity of staining (Figs 207 and 208) Transvers discoidal fragmentation was easily recognized (Figs 208 and 210) The necrot areas were walled off by a clear-cut zone of fibrous tissue (Fig. 209) but ther was complete absence of fibrosis in between the necrotic muscle fibres. In th more recent cases, the collagen fibres were loosely arranged, enmeshing a few re blood cells In the later ones, the fibres were densely packed especially at th

* The histological preparations and photomicrographs are the work of Dr E. Gutmann



1 206. Case G 12, 600 days after a traction injury ing the varying degree of re innervation even n a single nerve trunk. There is one thick nerve many empty Schwann tubes and a few thin ı. (Hypothetical period of re-innervation 483) See (*b*) *Traction Injury* p. 313



FIG. 207 Muscle fibres from an early case of necrosis. The nuclei are still visible, but there is variation in the intensity of the staining reaction in different muscle fibres.



iG 208. Discoidal fragtation and break-up of cle fibres in a necrotic ı. (Haematoxylin-eosin.)



FIG. 209 Cross-section of muscle showing a sharply defined area of necrotic muscle fibres surrounded by a zone of phagocytic and fibroblastic activity Note the dense acellular fibrosis at the periphery (Masson stain.)



FIG 21 Phagocytic[illegible] vity [illegible] break the fibres at the edge necrotic [illegible] of (Hortega silver [illegible] stain [illegible])



FIG. 211 Phagocytic activity leading to breakdown of the fibres at the edge of the necrotic mass of muscle. (Hortega silver carbonate stain.)



FIG. 212. Scattered fragments of necrotic muscle fibres within the connective tissue in an area of incomplete devascularization adjacent to an area of massive necrosis. (Masson stain.)



FIG. 213 Incom devascularization muscle, showing vasc connective tissue infilt ing between the mu fibres. Note the wavy c line of these muscle fib in some of which there an apparent increase in sub-sarcolemmal nuc These findings indicate t effect of denervatio (Hortega silver carbona stain.)



FIG. 214 Showing two adjacent areas of vascular damage, complete above and incomplete below Compare the sharp and ill-defined borders of the two regions. (Hortega silver carbonate stain.)



FIG 215 Regeneration of muscle fibres in an area of incomplete devascularization. Note the multi-nucleated and bulbous ends of the myotubes on the right.



[F]ig 216 Showing an artery with narrowed [lum]en and endothelial proliferation in an [are]a adjacent to a patch of necrosis. (Haema[tox]ylin-eosin)

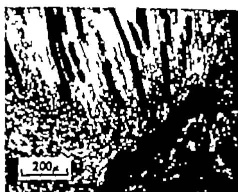


Fig. 217 Note the empty nerve trunk in centre, below a patch of completely necrotic muscle which has stained unevenly

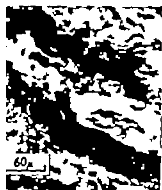


Fig 218 Empty Schwann tubes lying in connective tissue adjacent to an area of necrosis.



Fig 219 Nerve trunk adjacent to a necrotic area. Note the thin regenerating axons. (Ax.)



Fig 220 Dense intramuscular fibrosis. Note the muscle fibres scattered in the connective tissue.



Fig 221 Degenerated muscle fibres showing as homogeneous bands within connective tissue in which there are scattered nuclei.

(ii) *Conclusions*

The clinical features and pathogenesis of the lesions which were found has been discussed in some detail (Bowden and Gutmann 1949) The duration, nature and extent of the vascular damage are of primary importance in determining the lesions There was confirmation of Griffiths conclusion that the true Volkmann s ischaemia with massive necrosis was the result of deprivation of arterial blood supply There was also support for Parkes (1945) who stated there is little doubt that a form of muscle contracture clinically resembling the true Volkmann type, though probably without the typical histological picture, can occur from venous or capillary occlusions"

Parkes suggested that the susceptibility of the flexor muscles of the forearm to ischaemic lesions was due to direct involvement of their vessels in the spasm, and possibly to metabolic demands which differed from those of the extensors. There is evidence that the intramuscular vascular pattern is an important factor Campbell and Pennefather (1919) Power (1945) Le Gros Clark and Blomfield (1945) and Blomfield (1945)

The prognosis after a vascular injury will depend upon the relative masses of viable and non viable tissue, the possibility of regeneration of muscle and the state of its nerve supply The injury of the muscle may be associated with mechanical or ischaemic damage to the main nerve trunk, as well as with local lesions of the intramuscular nerves. There is, therefore, the additional problem of re innervation However if the bulk of the muscle has been irreparably damaged, the highest degree of re innervation would be useless. It is probable that dense interstitial fibrosis is irreversible. Clearly recovery after massive necrosis of muscle can only be the result of regeneration of the remaining viable muscles, or of recovery of previously denervated fibres.

(iii) *Summary*

(1) Three main types of histological change are found in association with contractures due to vascular damage of voluntary muscle in man. The muscles may show
 (*a*) Massive areas of necrosis surrounded by a clear-cut zone of fibrosis.
 (*b*) Dense interstitial fibrosis, without massive necrosis of muscle fibres. A few isolated fibres may be necrotic, while others may appear normal or show signs of denervation
 (*c*) Miliary necrosis with patchy interstitial fibrosis.
(2) The suggested aetiology of the three types of lesion is as follows
 (*a*) Massive necrosis due to deprivation of arterial blood supply
 (*b*) Dense interstitial fibrosis probably due to venous and/or capillary occlusion with oedema and late fibrosis.
 (*c*) Miliary necrosis with patchy interstitial fibrosis might be due to several factors which lead to slowly increasing tension within the muscle The hypothesis is that the rise of tension is sufficient to occlude the arterioles and thus lead to deprivation of arterial blood supply and subsequent necrosis.
(3) The vulnerability of certain muscles to vascular damage is related in part to the intramuscular vascular pattern
(4) The condition of the intramuscular nerve trunks varies they may be normal or show signs of Wallerian degeneration in areas where the muscle tissue is viable they may be necrotic and regeneration of axons can take place in favourable circumstances

(5) Functional recovery after ischaemic lesions depends mainly on the state of the muscle tissue and the state of its nerve supply

(6) There is evidence of regeneration of muscle fibres which may replace necrotic tissue to some extent, this process is probably dependent upon the efficiency of the intramuscular anastomoses

G CHANGES IN VOLUNTARY MUSCLE DUE TO PROLONGED EXPOSURE TO COLD OR IMMERSION IN COLD WATER

One of the earliest reports on the effect of cold upon voluntary muscle was made by Kraske (1879) who found evidence of necrosis of the contractile elements Blackwood and Russell (1943) made an experimental study of the effects of prolonged exposure to cold and immersion in water Blackwood (1944a) published a report on the histological changes in the tissues of the limbs of men who had suffered from exposure at sea There was one case in which the time between the beginning of immersion and the taking of the specimen was four and a half days. The muscle was taken three days after death from the foot of a man exposed for 34 hours in an open boat. The muscle showed patchy acute degenerative changes which Blackwood described as Zenker s hyaline necrosis. This was most marked at the periphery The affected muscles were friable and tearing of the tissue was thought to account for the numerous intramuscular haemorrhages which were seen not only in this case, but in all others examined by him Other specimens of human muscle were examined from 4 to 26 months after exposure The tissue showed mainly changes attributable to denervation with some necrotic muscle fibres and small foci of fibrous tissue replacement. In Blackwood s opinion this fibrosis was considered to be the result of repair of the tears in the muscle rather than the late result of an ischaemic infarct. The hyaline degeneration is of interest in that it was not found in early cases of simple denervation The presence of vascular damage might account for this and in addition all these patients had some degree of sepsis (cf Tower) The pattern of innervation was studied and in two cases there was evidence of delayed re innervation In addition to changes in the muscle, the nerve trunks were found to be damaged

H RE INNERVATION OF PROPRIOCEPTORS AND RECOVERY OF STRETCH REFLEXES

(i) *Experimental Observations*

Experimental observations upon the recovery of stretch reflexes after nerve injury have been made by Barker and Young (1947) They reveal the difficulties involved in assessment of return of proprioceptive function but show that a considerable stretch reflex (up to 60 per cent of normal) may return even after severance and suture of a nerve.

(ii) *Clinical Observations*

The return of reflexes after nerve injury has been estimated by testing the ankle jerks in a series of cases of injury to the sciatic nerve in man After suture of the nerve the ankle jerk either had not returned or was weak and sluggish even when the muscle was capable of voluntary contraction against gravity and sometimes strong resistance. These findings are in accord with the observations of Barker and Young.

No histological observations were made of re-innervation of muscle spindles in man in the biopsies reported in this section The omission is regrettable since

disorders of function particularly in the upper limb may well be partly du inadequate or inappropriate re-innervation of proprioceptors For exam a certain number of patients with recovering lesions of the median nerve ab the level of the elbow had difficulty in using the hand even though there was apparently adequate return of cutaneous sensibility and voluntary power T volunteered the information that they were unable to pick up small objects, h a cup or carry out skilled movements such as playing the piano with concentrated observation of the hand otherwise they have no idea of position of the fingers In such cases there was disturbance of joint posit sense, particularly in the terminal joint of the index finger Nevertheless, si there was also some disturbance of cutaneous sensibility this disability co be regarded only as presumptive evidence of defective re-innervation of p prioceptors

I CONTRACTURES OF MUSCLE

In surgical practice a contracture of voluntary muscle is defined as a shorten of the effective length of the muscle it limits the range of movement and n in time cause secondary changes in the relevant joints. The restriction of mo ment and the resultant deformity may in itself be a serious handicap even wh recovery from a peripheral nerve injury has been satisfactory Contractu associated with nerve injuries are to be found in the following circumstances

(1) Ischaemic lesions

(2) Local damage to a muscle belly with subsequent healing by fibrosis.

(3) Division of tendons which are subsequently repaired.

(4) Localized tetanus leading to irreversible contracture (Davenport Rans and Stevens 1929)

(5) In normal muscles which have remained shortened for long periods as result of stiff joints, improper immobilization or an uncorrect deformity These contractures lead to constant overstretching of t antagonists.

(6) In both denervated and re-innervated muscle

Some degree of contracture is probably inevitable in the first four types of ca but proper treatment should generally prevent it in the fifth and sixth

Contractures in denervated and re innervated muscle are of special intere As Tower (1939) points out, undue emphasis may have been laid on the pa played by the fibrosis which is found in denervated muscle from her ov observations and those of Buchthal Knappies and Lindhard (1936) she co siders that there are significant changes in the properties of the contract elements themselves. Thus at least two factors may be involved in the formation contractures of these muscles but a discussion of this point is beyond the scop of this report In a series of patients with radial nerve injuries studied at th Oxford Centre, it was observed that in the early stages of recovery or eve before the first sign of voluntary contraction there was a fairly sudden ons of shortening of the extensors. Electromyography suggested that this occurre in the early stages of re-innervation when fibrillation was declining an motor unit activity was beginning to appear These may possibly have bee

contractures as defined by physiologists, and they did not invariably disappear as recovery proceeded

The incidence of contractures after lesions of the various nerves with particular reference to treatment and splinting, will be described elsewhere The following example is instructive Two series of cases of suture of the ulnar nerve were investigated Patients in both groups had massage, exercises and passive movements in hospital Group A (125 patients) had been provided with ulnar nerve splints of the knuckle duster type and had been instructed to carry out passive movements several times daily in addition to using the hand actively the majority had electrotherapy for the intrinsic muscles Group B (227 patients) had no active splinting (see page 326) all had instructions to use and exercise the hand and many had night splints provided after contractures had appeared The incidence of contractures of the flexors of the 4th and 5th digits and joint stiffness in the two series is given below

Group	No of cases	Incidence of contractures		Incidence of joint stiffness		
				Whole series		Contracture cases
		No	%	No	%	%
A	125	37	29·6	11	8·8	29·9
B	227	170	74·9	102	45	60·6

The differences are very striking, and it is unlikely that electrotherapy would be responsible for the smaller number of contractures in group A In poliomyelitis the most important means of preventing contractures is known to be maintenance of normal muscle length by movements and by splinting. In group B the deformity was not corrected by the passive splinting at night and it is therefore possible that the more satisfactory result in group A was due to the employment of the knuckle duster splint From a detailed analysis of the two series it appeared that ischaemic lesions and local damage to muscle or tendon increase the tendency to contracture formation but this is not necessarily an invariable sequel to such injuries. Napier Barron Gregory and Thompson (1947) showed that corrective active exercises could be devised in a course of industrial rehabilitation.

J CRAMP

A number of patients with nerve lesions complained of severe and sometimes temporarily disabling cramp-like pain It was usually of short duration and was relieved by massage and stretching the affected muscles. The time of onset of the initial attack varied where the muscles were not wholly paralysed cramp was sometimes an early symptom, in the majority of cases it was of late onset during the period of recovery Cramp occurred only in muscles which were active, although not necessarily of normal strength The cases fell into two categories in one, cramp only occurred *during* activity and attacks were usually more frequent in cold weather *in the other larger* group cramp occurred at rest usually at night. Most of the patients in the latter group had injuries of the lower limb and the muscles most frequently involved were the hamstrings and calf Where cramp occurred during activity attacks could not be predicted with the certainty

found in typical cases of intermittent claudication Herniation of muscles was present in some of these patients and the attacks were diminished in frequency and intensity by wearing a suitable support. However herniation was not invariably associated with cramp

In both groups some of the affected muscles had suffered direct injury but again, damage to the muscle was not necessarily associated with cramp. A detailed analysis of these cases is being made, as the problem needs further investigation.

3 Splinting

A PRINCIPLES

Splints used in the treatment of peripheral nerve injuries belong to two main classes in the first the aim is to secure immobilization in the second to compensate for paralysis and encourage active use of the limb

Immobilization is required in the early stages of treatment to secure rapid healing of open wounds and of fractures, and after suture of nerves it is essential to prevent separation at the suture line. Trueta (1946) has shown the value of well fitting plaster casts and the need to elevate the limb to prevent oedema which if of long duration is followed by fibrosis and stiffness. Joints not immobilized should be fully exercised patients should learn to co-operate in this treatment from the beginning, particularly where there is a paralysis. Stiffness may lead to disaster (Fig. 225) The man whose hand is shown in this figure had injuries of the median and ulnar nerves at the wrist sensory recovery was complete, but the hand was a fixed and useless claw

Splinting for nerve injuries is designed to correct deformities, to prevent overstretching of paralysed or weak muscles to compensate as far as possible

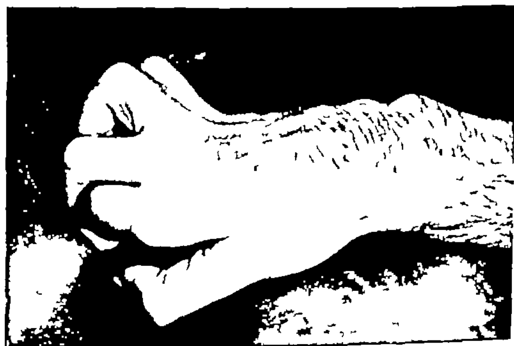


FIG. 225 Useless claw hand after injury of median and ulnar nerves sensory recovery was complete.

for the paralysis, to aid re-education and encourage active use of the injured limb throughout the period of disability As soon as an injury is recognized a temporary splint appropriate for the particular palsy should be added to the plaster (Bateman 1946) Fig 226 It should be impressed on the patient that the purpose of these appliances is to increase his activity not to restrict movement Splints should fit well be comfortable, light strong inconspicuous and easily cleaned simple in construction and use, and should produce no undue pressure on insensitive skin or underlying nerve trunks

The need for control of such deformities as drop foot is generally accepted but there are those who consider that for certain nerve injuries splints are not only unnecessary but harmful in that they hamper activity However active and passive exercise of the hand alone is not always sufficient to prevent contractures (see page 325) There is no doubt that in the past too much emphasis has been laid on the need for constant relaxation of paralysed muscle (Keith 1919) and limbs have been rigidly immobilized—sometimes with tragic results. There is no evidence that daily active and passive movements of joints through a full range is harmful, provided that chronic overstretching of paralysed muscles is prevented Sunderland (1948) showed that recovery of function was delayed by such overstretching and unfortunately there have been many instances of permanent impairment of function For example, in one follow up survey cases of median nerve injury were seen where no splinting had been employed The thumb had remained in the plane of the palm with consequent adduction extension and lateral rotation of the metacarpal In some cases, severe contractures had occurred in the tissues of the first interosseous space and in the carpo-metacarpal joint capsule. In ten a useful degree of sensory recovery had occurred In three the thenar muscles were felt to contract powerfully but produced no effective movement of the thumb although the contractures were not sufficiently severe to prevent it The muscles had evidently been stretched beyond the limits of efficiency thus leaving the patients with an unnecessarily severe disability (Napier 1952b) The part played by overstretching in the other unsplinted cases could not be accurately assessed though it is possible that some of the disappointing results of suture of the lateral popliteal nerve are partly due to chronic overstretching of the extensors, some of the patients having had no night splint or having failed to wear the one provided The same possibility arises in the case of unsplinted ulnar nerve injuries the final results of motor recovery in group B (page 325) were inferior to those of group A but other factors may have been involved

B TYPES OF SPLINT

(i) *Upper Limb*

Median nerve lesions The need for splinting has been indicated but where the opponens and flexor pollicis brevis are largely supplied by the ulnar nerve the tendency to deformity may be negligible and no splint is required The splint shown in Fig. 227 was designed by Highet (1942b) the disadvantage of this type is that, where strong traction is required to correct the deformity it may produce flexion of the wrist. However if employed early this difficulty should not arise. The splint shown in Fig. 228 was designed by Napier (1946) It is light and does not interfere with movement of the wrist it is made of soft material and diminishes the risks of pressure disturbances It is useless when deformities are fixed to any degree or where there is weakness or paralysis of the hypothenar





FIG 226 An example of a simple temporary splint in this case for thenar palsy

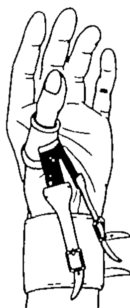


FIG 227 Splint for median nerve palsy (Highet).

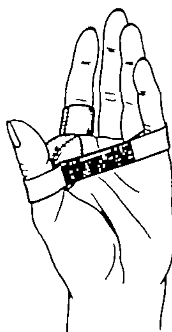


FIG. 228. Splint for median nerve palsy (Napier)

muscles. In both types of splint there is a tendency to produce f... metacarpo-phalangeal joint without full correction of the position of th... carpal Cholmeley (1946) designed a light and inconspicuous splint for ... pollicis paralysis, but it has the disadvantage of rigidity (Figs. ... a...

Ulnar nerve lesions The fixed knuckle-duster type of splint was d... Highet (1942b) it has been modified by Hendry (1945) Bunnell (1... Capener (1946) to permit active flexion and extension of the ... phalangeal joints (Fig. 231) As these splints do not restore the met... a further modification has been suggested If a cast is made of the h... correct position with restoration of the arch the bars can be curve...

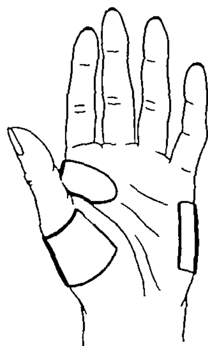


FIG 229 Plastic splint for thenar palsy (Cholmeley)



FIG. 230. D... Cholmeley ...



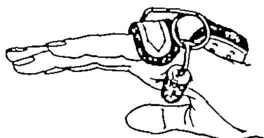


FIG 231 Modified 'knuckle duster' splint for ulnar nerve ... photographs of unsplinted and splinted ...

...viding ...nd in a bulkiness ... easily

hand and so maintain the arch A simple temporary splint can be made to the design described by Pruce (1946) (Fig. 232)

Combined median and ulnar nerve lesions Paralysis of all intrinsic muscles of the hand is a grave disability and it is therefore essential to supply the patient with some form of active splint One of the most simple and effective is shown in Fig. 233

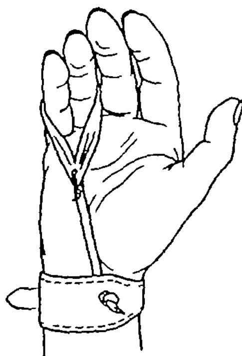


FIG 232. Temporary splint for ulnar nerve palsy (Pruce).

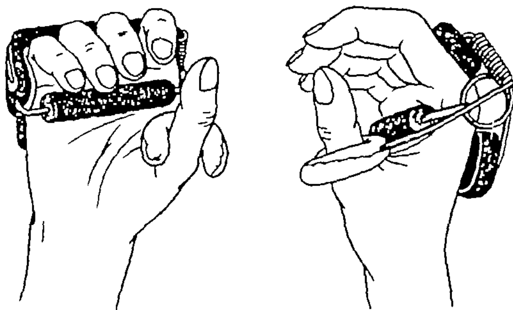


FIG 233 Splint for combined median and ulnar nerve palsies. The thumb can be actively extended and abducted in the plane of the palm. (Attachment for thumb designed by Mr G Baker Wingfield Morris Orthopaedic Hospital Workshops.)

Brachial plexus injuries

Upper roots of the plexus The adjustable abduction splint of Highet (1942b) is light and comfortable the shoulder is held in abduction and flexion and the movable joint at the elbow is a great advantage (Fig 239) It is possible to prevent contractures of the biceps and to alter the rotation of the shoulder at will Lack of external rotation of the shoulder is too frequent a sequel and reduces the value of any recovery in the deltoid

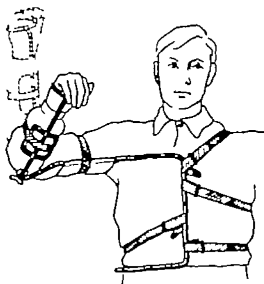


Fig. 239 Abduction splint with adjustable elbow piece.

Lower roots of the plexus The prognosis after degenerative lesions of the lower roots of the plexus is poor so far as the intrinsic muscles of the hand are con cerned and the decision to splint the hand must be made on the merits of each individual case. The combined median ulnar and radial splint may be worn to combat the tendency to form contractures of the long muscles.

(ii) *Lower Limb*

Highet (1942b) pointed out the necessity of allowing movement at the ankle joint in sciatic nerve injuries. Four types of splint which permit this are illus trated Fig. 240 this splint is simple and light but has the following dis-advantages prolonged pressure from the cuffs leads to wasting of the quadriceps (Fig. 241) and the foot is unstable for walking on uneven surfaces The splint conspicuous and damages the trouser leg.

Fig. 242 this splint provides stability with single or double side irons The ring attached to the shoe is conspicuous and damaging to clothes but there more serious objections a callosity almost invariably forms under the medial lateral attachment of the spring to the shoe and may go on to form an ...ble ulcer A varus or valgus deformity of the foot is not always effectively ...d and the shoe may become distorted (Fig. 243) The lower limb tends ...lly rotated when the spring is placed laterally thus aggravating the any valgus deformity of the foot. If the spring is sufficiently tight to drop undue pressure is applied to the calf muscle. This causes dis- ...d leads to some wasting of the muscle Traction on a loose cuff may

hand or leave the wrist free provided that the wrist-drop and lateral deviation of the hand can be controlled the free wrist is desirable, but a serious fixed hyperextension of the metacarpo-phalangeal joints may occur if the splint is improperly applied or used by an unintelligent patient

The Oppenheimer type of splint (Fig. 237) described by Bunnell (1946) is light and inconspicuous but cases have been seen when there were symptoms of pressure on the digital nerves though only where a heavy type was worn On the whole the splint with coiled spring wire extensions for individual digits which was designed by Capener combines the greatest number of advantages it gives free movement of the wrist and digits and is light and easy to clean. It is, however somewhat bulky and conspicuous. The Perspex splint designed and made in the Rehabilitation Department of Vauxhall Motors, Ltd. (Fig. 238) is light, fairly inconspicuous, easily made and cleaned The disadvantage of this appliance is that it prevents active flexion of the wrist.

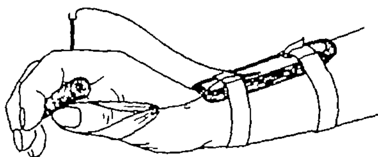


FIG. 236. Radial nerve palsy splint (Thomas)

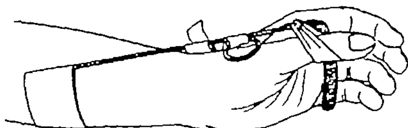


FIG 237 Oppenheiman type of splint for radial nerve palsy (described by Bunnell)

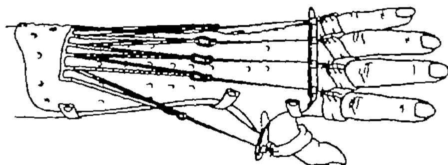


FIG 238 Perspex splint for radial nerve palsy Splint made and designed in the Rehabilitation Training Shop of Vauxhall Motors, Ltd. (Reproduced by courtesy of the Consultant Orthopaedic Surgeon, Mr H. H Newell.)

Fig. 244 this splint is less conspicuous and in the experience of patients who have worn this type and the one just described it is more comfortable more efficient in correcting the foot drop and less damaging to clothes. Callosity formation is not so frequent. If a single iron is used with or without a T-strap regular supervision is required, particularly during recovery after a complete sciatic palsy Loss of balance may develop between the evertors and invertors, with a consequent tendency to varus or valgus deformity With adequate control of the heel and suitable insoles, these deformities should not become serious

Fig. 245 Capener (1946) has produced an even lighter and springier splint It is simpler and less expensive in construction and has no disadvantages except that it is liable to snap after prolonged use In the last two types of appliance the spring can be reversed for use in isolated medial popliteal injuries with paralysis of the calf muscle

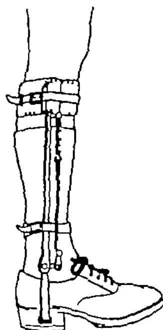


FIG 244 Toe-raising spring with side iron jointed at the ankle and fitted into a slot in heel of the shoe.

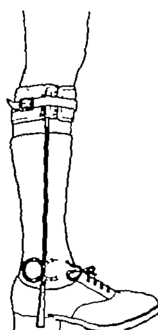


FIG 245 Coil spring appliance for foot-drop (Capener). Reversal of the direction of the spring will correct the calcaneous deformity due to an *isolated medial popliteal palsy*

Paralysis of the intrinsic muscles of the foot Metatarsal pads and Perkins platforms are not always necessary but if there is a marked tendency to clawing or hypertension of the toes a suitable pad should minimize contracture formation and damage to the skin from friction by footwear It may be advisable to extend the insole with a firm thin piece of leather going into the toe of the boot, thus preventing the slipping that is liable to occur and cause discomfort and abandonment of the insole.

4 Electrotherapy

Histological studies have shown that progressive atrophy of denervated muscle fibres and proliferation of interstitial fibrous tissue are two important factors which influence recovery of motor function. It is therefore desirable to prevent or minimize these adverse changes though as yet there is no general

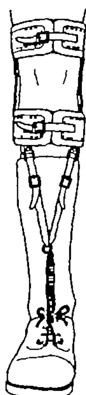


Fig 240. Toe raising spring without side irons.



Fig 241 Wasting of quadriceps from prolonged use of toe-raising spring shown in Fig. 240. (Tracing from photograph)

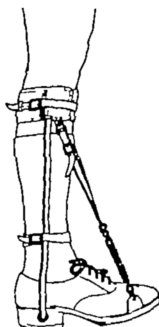


Fig 242. Toe raising spring with single or double side irons fitted into round socket in heel of shoe.

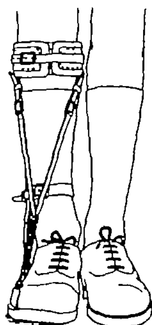


Fig. 243 Valgus deformity of foot and distortion of shoe. Unless the foot was pulled into this position the appliance failed to correct the foot-drop. A T-strap controlled heel but did not prevent distortion of forefoot. (Tracing from photograph.)

lead to chafing of the skin On the other hand a tight cuff has been known to cause a lesion of the internal saphenous nerve in a few cases It is also possible that such pressure has damaged the lateral popliteal nerve as it winds round the neck of the fibula

and no attempt was made to avoid fatigue during exercise. Even after maximal treatment of one hour daily no adverse effects were found Weak contractions were less effective in minimizing atrophy Histological examination showed that fibrosis was less conspicuous and muscle fibres were larger in diameter in treated muscles these findings were more conspicuous near the surface of the muscle where the effect of treatment was presumably maximal Although the main effect of treatment was seen during denervation there were demonstrable differences in treated recovering muscles, and they were seen four months after cessation of the galvanic exercise. There was no definite evidence that the time of onset of recovery was influenced by treatment, but the degree of recovery was higher in treated animals

Conclusions In the rabbit it is possible to delay and minimize atrophy by galvanic exercise, provided it is begun sufficiently early after denervation and vigorous contractions are elicited Daily treatment of 20 to 30 minutes duration gave the best results The negative results of Langley (1916) Langley and Kato (1915) Chor Cleveland Davenport, Dolkart and Beard (1939) Molander and Steinitz (1941) and other workers were explained as being due to the inadequacy of the strength and number of the contractions elicited

B CLINICAL INVESTIGATIONS

Doupe, Barnes and Kerr (1943) investigated the effect of electrical stimulation on the circulation in and recovery of denervated muscle.

Material and methods The progress of motor recovery was recorded in twelve cases following suture at different levels of the radial or posterior inter osseous nerves. The longest period of delay before suture was 10 months and there was one primary suture. (The extent of the resection was not stated) Patients were examined over periods ranging from seven months to two years Treatment consisted of 15 to 30 moderate contractions of each muscle given five to six times a week five cases were untreated, one had one month s treat ment, and the remainder had five months or more. In all cases a short cock up splint was applied to prevent wrist drop the digits being unsupported Ten cases had massage three to five times weekly for six to eight months

Results No significant difference in the rate of recovery was noted in those patients who received treatment, which is in agreement with the experimental findings of Gutmann and Guttmann (1942b 1944) In two untreated cases the period of observation was too short to permit of any conclusions being formed on the final quality of recovery From the data presented there appears to be a slightly higher degree of recovery in the radial extensors in those patients who received electrotherapy The numbers are, however small and there are several important variable factors that were not taken into account, such as the length of resection

Discussion and conclusions The authors concluded that electrotherapy in the form given had no beneficial effect on the return of motor power They suggested that the failure to achieve satisfactory results in man might be due to an insufficient amount of work being imposed on the muscle. Since an increase in blood flow is caused by muscular work plethysmographic studies were made to estimate the change of blood flow associated with electrically induced activity Three patients were examined Paralysis was complete in the segment of the limb to which the cuff was applied Control measurements were made on the normal limb on another occasion after resting for one hour The resting blood flow was greater in the denervated muscles and the effect of galvanic

agreement on the best means of doing so In 1841 Reid first advocated the treatment of paralysed muscles by galvanic stimulation. Since then many observers have studied the effects of electrotherapy amongst the more notable recent contributions are those of Fischer (1939) Eccles (1941 1944) Hines, Thomson and Lazere (1942) Hines (1943) Solandt, de Lury and Hunter (1943) Osborne and his colleagues (1944) Some consider that it is not only useless but harmful, leading to damage and excessive fatigue of the denervated muscle. In 1920 the report of the Medical Research Council Peripheral Nerve Injury Sub-committee recommended the treatment of "individual paralysed muscles by the weakest effective galvanic and faradic currents" However as conflicting evidence continued to accumulate further experimental and clinical investigations were undertaken at Oxford and Winwick.

A EXPERIMENTAL INVESTIGATIONS

Gutmann and Guttmann (1942b 1944) investigated the influence of electrotherapy on denervated muscles in the rabbit.

Methods In the first experiments six animals were used and in the second 30 The muscles studied were those supplied by the lateral popliteal nerve. In the first investigation both lateral popliteal nerves were crushed with fine forceps in four animals in the remaining two both nerves were cut at the same level and joined with plasma (Medawar and Young, 1940) In the second investigation the experiments were divided into two groups (*a*) Treatment was applied to permanently denervated muscle the lack of re innervation was confirmed by biopsy and a distinction was made between muscles denervated for short and long periods (*b*) Treatment was applied to muscles in which re innervation occurred after crushing the nerve, after section and primary suture, and after section and delayed suture by cross union Galvanic stimulation was employed in all experiments the untreated muscles on one side were used as controls for the others. The effects of varying the strength of the current, the duration of each treatment and the delay before beginning the course of treatment were studied The circumferences of the legs were measured at fixed points on the limbs at weekly intervals. The thresholds of direct percutaneous faradic stimulation were measured occasionally and the time of onset of functional recovery as judged by the return of the spread reflex, was noted in each case At the end of the course of treatment the animals were anaesthetized and the muscles of both legs were exposed. The macroscopic appearance of the muscles, the presence or absence of fibrillation and the response to direct faradic stimulation were recorded The muscles were excised and weighed The bulk and weight of muscle were taken as a measure of the degree of atrophy but, as the authors stated, this was not a wholly satisfactory estimate of atrophy of the contractile elements because all constituents were included Histological studies were made of the treated and untreated muscles and the mean diameter of comparable samples of muscle fibres was calculated

Results It was found that the rate of atrophy was most rapid in the early stages of denervation although it continued throughout 150 days, the longest period of denervation observed in these experiments Atrophy was not wholly prevented but was delayed and diminished by adequate galvanic treatment during denervation and in the early stages of recovery The effect of treatment was greatest during the first four weeks thus the earlier it began after denervation the greater its influence. The most satisfactory results were obtained with daily exercise of 20 to 30 minutes duration Vigorous contractions were elicited

exercise was minimal (The rates of stimulation were high 240 a minute in two cases and 30 and 60 a minute in the third Since the number of cases is small, a repetition of this investigation is necessary possibly using slower rates of stimulation.) The conclusion reached was that electrotherapy did not aid recovery except in so far as it assisted re-education and maintained mobility of the tissues.

Jackson (1945) investigated the value of *galvanic treatment of the paralysed* intrinsic muscles of the hand.

Material and methods One hundred and sixty one patients with ulnar or combined median and ulnar nerve lesions were studied. The wasting of the hand was estimated from time to time by a simple volumetric method Patients were divided into two groups one treated with galvanism and the other untreated The rate of wasting in the two groups was compared and of the 161 patients 92 were examined sufficiently frequently to make the data reliable. The lesions ranged from gunshot wounds with gross trauma, sepsis and complete division of the nerve to lesions in continuity caused by closed fractures or dislocations. Few cases were admitted shortly after injury and some a year or more later On admission a full history was taken and all patients were submitted to the routine clinical examination which included testing of electrical excitability and, in some cases electromyography The cases were grouped in the following way

Type of nerve lesion	1 Division
	2. Lesion in continuity (with a sub-division, traumatic ulnar neuritis)
Level of lesion	1 High—proximal two thirds of arm or higher
	2. Medium—distal one third of arm and proximal one half of forearm.
	3 Low—distal half of forearm and hand
Length of history	1 Early—less than six months between injury and first volumetric reading.
	2. Fairly early—between six and twelve months.
	3 Late—over twelve months

Treatment All cases were treated by passive movements, massage and occupational therapy Active exercises were given for the normal muscles throughout the period of treatment and the affected muscles were also actively exercised once recovery occurred Paralytic deformities were corrected with active splinting. *In the treated cases galvanic stimuli were applied to individual* paralysed muscles. The course of treatment was given six days each week, stimuli being given at the rate of 30 a minute, and adequate time was allowed for the muscles to relax between contractions. Three groups of 30 contractions were elicited from each muscle, with an interval of at least one minute between each group The aim was to obtain contractions of sufficient strength to move the appropriate joints freely when gravity was eliminated The strength of the current was limited by the tolerance of the skin and of the individual patient. In addition to the volumetric measurements records were kept of the recovery and degree of voluntary power the ability to use the recovering muscles independently and of electrical excitability and electromyographic activity The variable factors were studied and the intrinsic error of the apparatus (0·5 per cent) was taken into account. The volume of the hand is subject to variation with temperature use of the hand, treatment and venous obstruction. However large changes were brought about only by abnormal conditions the

variations due to normal activity were small though they made individual readings somewhat unreliable There was some correlation between changes in volume of the two hands of the same subject hence corrections for these could be made by measuring both hands

Results The rate of wasting was greatest within the first 100 days after denervation and gradually decreased Where no galvanism was given wasting continued for about 400 days and after this time the volume of the hand became constant. If galvanism was given wasting was diminished but not prevented in the first 100 days, and ceased in the 100 to 200 day period Immobilization appeared to increase the rate of wasting when the muscles were untreated the effect of galvanism was therefore even greater in these cases than in those with the limb free It was found that treatment was of little value if given less than three times weekly and the effect was lessened if attendances were irregular The recovery of function was on the whole better in muscles in which there was little wasting whether or not treatment had been given In the few children studied recovery of power and bulk of the muscles was satisfactory whether or not galvanism had beeen given There was some evidence to suggest that treat ment aided recovery when it was given at the time of re-innervation

Some substantiation of the value of treatment was obtained by examining the results of suture of the ulnar nerve in two large series of cases In one group the majority of patients received galvanic treatment and in the other less than 7 per cent of patients received any form of electrotherapy Recovery was of poorer quality in the latter group

Conclusions There is conclusive proof that regular and adequate galvanic treatment is effective in diminishing atrophy and encouraging recovery of the intrinsic muscles of the hand, provided it is given sufficiently soon after denervation. Windows should therefore be made in plasters so that treatment can be instituted at once and continued during the period of immobilization.

The Rôle of Galvanism in the Treatment of Larger Muscles

Large muscles may show less response to treatment than small ones in view of the greater bulk of tissue to be stimulated and Eccles (1941) has shown that in animals there are differences in response in different muscle groups. A small investigation of the effect of galvanism on the atrophy of muscle in radial nerve paralyses was made (to be published) the method used being the same as that employed by Jackson (1945) The disadvantages of volumetric measurement are increased in these cases since the bulk of denervated muscle is small in comparison with the total bulk of the forearm and hand The differences in volume which were obtained in treated and untreated cases were not statistically significant These cases were reviewed from the point of view of rates of recovery and the final grade of recovery and again treatment appeared to have no significance

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In deciding upon a course of treatment it is clear that the circumstances of each patient must be reviewed If he is to lose a permanent situation or training, it may be wise to forego electrotherapy unless arrangements can be made to supply him with a stimulator for treating himself at home. If possible treatment should not be omitted in cases of paralysis of the intrinsic muscles of the hand Treatment should be given daily for choice and not less than thrice weekly A good contraction must be elicited and faradism is therefore useless for denervated muscle Treatment consisting of 90 contractions daily for each

exercise was minimal (The rates of stimulation were high 240 a minute in two cases and 30 and 60 a minute in the third Since the number of cases is small, a repetition of this investigation is necessary possibly using slower rates of stimulation) The conclusion reached was that electrotherapy did not aid recovery except in so far as it assisted re-education and maintained mobility of the tissues.

Jackson (1945) investigated the value of galvanic treatment of the paralysed intrinsic muscles of the hand.

Material and methods One hundred and sixty one patients with ulnar or combined median and ulnar nerve lesions were studied The wasting of the hand was estimated from time to time by a simple volumetric method. Patients were divided into two groups one treated with galvanism and the other untreated The rate of wasting in the two groups was compared, and of the 161 patients 92 were examined sufficiently frequently to make the data reliable. The lesions ranged from gunshot wounds with gross trauma, sepsis and complete division of the nerve to lesions in continuity caused by closed fractures or dislocations Few cases were admitted shortly after injury and some a year or more later On admission a full history was taken and all patients were submitted to the routine clinical examination which included testing of electrical excitability and, in some cases electromyography The cases were grouped in the following way

Type of nerve lesion	1 Division.
	2. Lesion in continuity (with a sub-division, traumatic ulnar neuritis)
Level of lesion	1 High—proximal two thirds of arm or higher
	2. Medium—distal one third of arm and proximal one-half of forearm.
	3 Low—distal half of forearm and hand
Length of history	1 Early—less than six months between injury and first volumetric reading.
	2. Fairly early—between six and twelve months.
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Treatment All cases were treated by passive movements, massage and occupational therapy Active exercises were given for the normal muscles throughout the period of treatment and the affected muscles were also actively exercised once recovery occurred Paralytic deformities were corrected with active splinting In the treated cases galvanic stimuli were applied to individual paralysed muscles. The course of treatment was given six days each week, stimuli being given at the rate of 30 a minute and adequate time was allowed for the muscles to relax between contractions. Three groups of 30 contractions were elicited from each muscle, with an interval of at least one minute between each group The aim was to obtain contractions of sufficient strength to move the appropriate joints freely when gravity was eliminated. The strength of the current was limited by the tolerance of the skin and of the individual patient. In addition to the volumetric measurements records were kept of the recovery and degree of voluntary power the ability to use the recovering muscles independently and of electrical excitability and electromyographic activity The variable factors were studied and the intrinsic error of the apparatus (0·5 per cent) was taken into account. The volume of the hand is subject to variation with temperature, use of the hand treatment and venous obstruction However large changes were brought about only by abnormal conditions the

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muscle or muscle group is effective In Jackson s series of cases the contractions were unresisted and the hands were supported to minimize the effect of gravity The part played by various conditions of tension was discussed briefly by Young (1946) who concluded that the optimal form of treatment was probably one in which the contractions were elicited against moderate resistance, but the question has not yet been settled conclusively Faradism is of value for training muscle after transplantation and also for exercise after recovery from nerve injury if this is required Young children are intolerant of treatment and as the results are good in its absence the matter should not be pressed

D TYPE OF CURRENT TO BE EMPLOYED

The current employed in these investigations was galvanic The patients varied in their tolerance to treatment, which at times gave discomfort. Solandt de Lury and Hunter (1943) suggested that sinusoidal current is of more value. However Hines, Thomson and Lazere (1942) considered that any current producing a good contraction is effective. Hines (1943) and Fischer (1939) believed that the beneficial effect was one of training in the sense used by athletes They showed that fatigue and stretching of muscle during treatment were not harmful the same views were expressed by Gutmann and Guttmann (1944) A balanced current has the merit of eliminating electrolytic changes and two types of machine delivering such impulses are now available The question of relating the type of stimulus to the changing excitability and contractility of muscle has been discussed by Grodins, Osborne, Johnson Atana and Ivy (1944) and by Kosman, Osborne and Ivy (1947)

5 Changes in Skin during Denervation and Re-innervation

In this section it will be necessary to consider only those factors which particularly influence the recovery of function

A ULCERATION AND CALLOSITY FORMATION

Ulceration, the formation of callosities and atrophy of the pulp of the digits are three trophic changes which may profoundly influence functional recovery The seriousness of the first is well recognized and has been attributed to repeated trauma in denervated areas Doupe and Cullen (1943) suggested that the intractability of trophic ulcers was due to oedema rather than to denervation. In a large follow up clinic it has been found that the most frequent complaint from patients with sciatic nerve injuries has been of chronic discomfort from callosities Both these and trophic ulceration have been aggravated by ill fitting shoes unsuitable foot supports and certain types of appliance. It is likely that the incidence of callosities, ulcers and even amputations might be reduced by attention to these points, coupled with education of the patient and regular chiropody

Atrophy of the pulp of the digits is significant in the hand for it increases the difficulty of picking up small objects Since there is little information about the underlying cause the basis for prevention or treatment is lacking. However the disability may be reduced by keeping the nails a little longer than normal thus turning to good account the increased longitudinal curvature of the finger nails which accompanies atrophy of the soft parts.

B CHANGES IN SENSIBILITY

The sensory phenomena observed after degenerative lesions of nerves and during the phases of recovery from different types of lesion are now well known though not well understood Head's observations, presented fully in his collected works (1920) have not been entirely confirmed but the findings of Trotter and Davies (1909 1913) and Boring (1916) are generally accepted In the last 12 years Woollard his pupil Weddell and others have shed further light on the neurohistological basis of normal and abnormal cutaneous sensibility Since perfect recovery of sensation is dependent upon restoration of the normal pattern of innervation a brief account of the normal state must be given

(i) *Neurohistological Basis of Cutaneous Sensibility*

Histology The pattern of cutaneous innervation has been studied by many workers, but much of the detail remained unknown and the problem was investigated afresh by physiological and histological experiments. Silver stains and intravital staining by methylene blue were used by Weddell and his collaborators It is well known that branches from the main cutaneous nerves form a deep and superficial plexus in the dermis The course of some individual nerve fibres within the plexus was studied and they were seen to divide repeatedly and form a net like meshwork. For example, a single pain fibre was found to innervate a circular area on the dorsum of the hand as large as 0·75 cm. in diameter There is reason to believe that the size of such terminal pain nets varies in different parts of the body A single nerve fibre bears numerous endings which are invariably of the same type and it is evident that a sensory neurone with its processes and endings forms a sensory unit in the same way that a motor neurone forms a unit with the muscle fibres supplied by it This concept was first enunciated by Boring (1916) and amplified by Tower (1935b 1940) and Walshe (1942) The punctate nature of cutaneous sensibility has been well recognized Weddell (1941b) was able to show that a sensory spot sometimes consists of groups of endings innervated by more than one nerve fibre of the same type approaching from different directions. The number of such spots is greatest in areas of acute sensibility In addition to the myelinated fibres on which the encapsulated endings are found in touch and cold spots, non myelinated accessory fibres also innervate these spots Similar accessory fibres are found round hair follicle endings.

By correlating the results of sensory testing with histological findings in the rabbit and man Woollard Weddell and Harpman (1940) concluded that the extent of the overlap of fibres subserving a particular modality of sensibility was a measure of the minimum distance at which two points would be perceived individually Woollard *et al* (1940) established the fact that pain sensibility is subserved by the free endings of fine nerve fibres in the deeper layers of the epidermis (the stratum mucosum and stratum granulosum) They showed that both normal and so-called protopathic pain could be aroused in normal skin and suggested that the protopathic pain was the result of stimulating several fibres of the same plexus. The greater intensity and diffuse character of this protopathic sensation were thus explained on the basis of spatial summation It is suggested that the fine beaded accessory fibres might be considered to be protective in function, because an unduly intense stimulus would excite these fine non-medullated fibres and give rise to a painful sensation

As each sensory spot is innervated by several fibres approaching from different directions, "a single stimulus at the periphery is presented to the spinal cord as a complex spatial and temporal pattern of impulses" (Weddell, Sinclair and Feindel, 1948)

Our concepts of cutaneous sensibility have not reached finality but, as Walshe points out in his critical reviews (1942, 1948) they are built on a more sure anatomical and physiological foundation since Woollard and his successors elucidated the pattern of cutaneous innervation Numerous observers have postulated that specific modalities of sensibility are subserved by characteristic nerve endings. Walshe (1942) goes further than this, for on the basis of anatomical physiological and clinical evidence he believes that the whole sensory pathway from the periphery to the ultimate central destination of impulses is specific for each modality

(ii) *Regeneration of Cutaneous Nerves in Animal Experiments*

(*a*) *Histological findings after section of nerve*

There is persistent abnormality of reaction to methylene blue in Schwann cells of degenerated pathways. Large numbers of collateral fibres are found during the process of regeneration and the diameter of the axons appears smaller than normal for a considerable time However no quantitative data are available and no time course was given by Weddell and Glees (1941) In the nerve trunks there are numerous empty Schwann tubes in the early months of regeneration, presumably due to the fact that fewer axons penetrate the scar after section of the nerve. Hair follicles are innervated by unusually fine fibres. The subcutaneous nerve nets tended to be isolated and sparse without overlap in the earlier stages of regeneration. Later the density of the nerve nets may appear normal

Correlation of the results of sensory tests and histological findings Sensory testing was carried out by the use of faradic stimuli and pin pricks in lightly anaesthetized animals. When fibres were stained with methylene blue the regenerating axon tips were found to be 5 mm. in advance of the area from which a nociceptive response was obtained Where recovery was thought to be due to ingrowth of adjacent normal nerves a discrepancy of only 1 mm. was observed between the histological findings and the point at which there was a functional response It was suggested that in the latter areas the advance of axon tips was so slow that maturation proceeded at almost the same rate. In recently re innervated skin after a single crushing of the nerve the number and intensity of stimuli required to evoke a nociceptive response was greater than normal (precise time relationships are not given) After section this finding was even more striking and there was a notable latent period for the response. In the later stages little abnormality was detected by this crude method of stimulation. Where a prick and faradic stimulation just produced a response Weddell found that hair follicles were sometimes supplied only by a single nerve fibre, nerve nets were isolated and did not overlap and there were numerous empty Schwann tubes.

(*b*) *Factors influencing recovery of sensibility*

Weddell, Guttman and Gutmann (1941) suggested that, in the rabbit, recovery of sensibility was due to three factors, overlap by adjacent fibres, active ingrowth of adjacent fibres and regeneration of the injured nerve.

Recovery by overlap It was suggested that early recovery of sensibility in the

periphery of areas of analgesia is first due to resumption of function in the remaining normal fibres derived from overlapping adjacent nerves Whilst there is evidence of three phases in the recovery of sensibility the interpretation placed by Weddell *et al* on the first raises some difficulty It may well be argued that the term recovery by overlap is inappropriate since the nerve fibres are stated to be normally present in the affected area. It is hard to understand why injury to an adjacent nerve should lead to temporary suppression and later resumption of function in these normal nerve fibres. In the rabbit the early recovery thought to be due to overlap generally occurs within 2 to 4 weeks after section of a nerve although this might take place in a matter of days in young animals. Gutmann and Guttmann (1942a) considered that recovery in zones of overlap is retarded by infection trophic sores, age and by local damage to skin supplied by adjacent nerves

Active ingrowth of adjacent fibres Continued shrinkage of the area of analgesia and anaesthesia was found to be due to active ingrowth of adjacent fibres. In young animals this process was more active than in the older ones Local extension may be considerable but does not wholly replace the process of regeneration of the main nerve supplying a large area

Recovery by regeneration Whilst recovery due to regeneration of the damaged nerve fibres proceeds in a general downward direction it was observed that recovery is faster at the edges of an analgesic area, so that there is a concentric shrinkage of sensory loss Gutmann and Guttmann (1942a) and Weddell (1942) thus confirmed the earlier observations of Trotter and Davies (1909 1913) and of Boring (1916) which had been made on man

Nature of lesion Gutmann and Guttmann (1942a) found that the nature of the lesion influenced the rate and degree of recovery After a single crush of the lateral popliteal nerve functional recovery proceeded at an average rate of 3·35 mm. a day with a latent period of 22 days After suture this rate was 2 46 mm a day with a latent period of 40 days The degree of functional recovery after suture is variable and always inferior to that following a single crush at the corresponding level (Weddell s observations are in agreement with these findings) Crushing over a considerable length of nerve leads to results similar to those found after section and suture.

Level of lesion Gutmann and Guttmann (1942a) found that the rate of functional recovery was more rapid in low lesions than in those inflicted at high levels. They tentatively attributed this to the scattered arrival of regenerating fibres coming from greater distances Information about changes due to prolonged denervation of organized sensory endings is lacking. If changes do occur the greater delay in re innervation after a high lesion would lead to more advanced atrophy of the endings with resultant defects in functional recovery

(iii) *Functional Results of Nerve and Root Section in Man*

When a peripheral nerve has been divided the area of loss of pain is less extensive than the loss of touch On the other hand if a nerve root is sectioned sensations of touch pain cold and warmth are lost concentrically the loss of touch being least extensive These observations have been made by many workers, of whom Foerster was one (1925 1927 1929b 1933) and they were confirmed by Weddell (1941a) In both types of injury the localization of stimuli and two point discrimination are poor in the intermediate zones of overlap and there is subjective abnormality in sensation (Cf Trotter and Davies 1909 1913 Head 1920)

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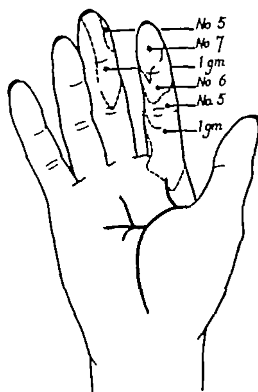


FIG 246. Result of examination with graded von Frey hairs two years after suture of the digital nerves to index and radial half of middle finger Note the progressive size in threshold towards the tips of the digits. Dashes denote the boundary of the area of anaesthesia to the particular hair indicated 1 gm. hair is No 3 in this series.

(a) Correlation of histological and functional tests during regeneration

Woollard *et al* (1940) observed the regeneration of cutaneous nerve fibres below an ulcer which had been produced experimentally in a normal individual, and found that with the regeneration of naked axons there was a return of pain sensibility Weddell (1941a) examined biopsies from a patient with a recovering sciatic lesion. In areas where pain alone was evoked by stimulation there were no thick nerve fibres and no organized nerve endings were seen. There were however fine nerve nets. Where pain and touch were appreciated there were thick nerve fibres round the hair follicles and fine nerve nets were also present In another patient who had a tube pedicle graft, thin nerve fibres were found in the region where there had been a return of pain sensibility

(b) Factors influencing recovery of sensibility

It has been suggested that recovery of sensibility in man is due to resumption of function in those fibres of adjacent nerves which overlap with the damaged nerve, to active ingrowth of adjacent normal fibres and to regeneration of the injured nerve fibres. There is clinical evidence of three phases of recovery of sensibility but the objections considered above are equally applicable here to the interpretation placed on the earliest phase of recovery There is however no doubt about the nature of the regenerative processes underlying the two latter phases The phenomenon of recovery by active ingrowth from adjacent nerves was first observed by Pollock (1920) Highet (1942a) and Livingston (1947) have subsequently reported cases in detail Napier (1952a) has shown that in full thickness skin grafts recovery by ingrowth from adjacent normal skin is the common process of re innervation.

Nature of lesion The influence of the nature of the lesion in the main nerve trunk upon functional recovery was clearly demonstrated by Seddon (1943) After a pure axonotmesis a perfect functional result was gradually obtained Recovery was slower and of inferior quality after nerve suture localization, stereognosis tactile and two-point discrimination were defective. Between these two types of recovery there are many intervening grades presumably this varies according to the severity of the intraneural damage.

Level of lesion Zachary shows in this report (p 368) that the final recovery after suture at a high level is less satisfactory than that obtained after suture at a low level.

Delay in repair and long resections Zachary has also shown that delay in repair and long resections both contribute to an unsatisfactory result. In the case of motor recovery progressive atrophy of denervated muscle is a significant factor but at present there is no histological study of the pattern of cutaneous re innervation with varying periods of denervation.

Age No definite conclusions can be drawn at present since the numbers of cases of peripheral nerve injuries in children are relatively small and there are many variable factors. Nevertheless, the impression is that the quality of sensory recovery is better in the young

(iv) *Conclusions*

The normal pattern of cutaneous innervation is complex and it follows that complete recovery of function must depend not only upon restoration of the anatomical pattern of cutaneous innervation but also upon a restoration of the normal pattern of impulses transmitted to the central nervous system. This would demand re innervation by adequate numbers of appropriate nerve fibres

of a sufficient degree of maturation to transmit impulses at the normal speed and frequency From his experimental observations Weddell (1942) concluded that from a histological point of view the extent of re innervation depends upon the number of nerve fibres in a given nerve trunk and also upon the number of collaterals derived from the proximal axons. Whilst the formation of large numbers of these collaterals potentially increases the chances of penetration of the distal stump and re-innervation of end-organs, it affords no guarantee of normal sensibility even in the presence of re innervation which is considered numerically and histologically complete This is exemplified by those patients in whom sensibility has returned throughout the autonomous zone of a nerve but in whom careful testing reveals subjective and objective abnormalities The threshold of stimuli may be raised as in the case illustrated in Fig 246 This man was tested with graded von Frey hairs it can be seen that there was a definite rise in threshold towards the tip of the index finger and there were also qualitative abnormalities. Cross reference of stimuli can be explained on the basis of misdirection of axons and Weddell offers an explanation for some of the subjective abnormalities encountered during regeneration Since a normal sensory spot may be innervated by several nerve fibres approaching from different directions it is clear that during regeneration there may be a phase in which such a spot is innervated by a single fibre only If this were the case there could be no spatial summation and the reaction might well be of the explosive all or none type without localization or grading.

The recovery of function is influenced to varying degrees by loss or abnormality of sensibility The effect will depend not only upon the nature of these changes but also upon their distribution and upon the occupation and temperament of the patient. Abnormal and unpleasant sensation is a strong deterrent to free use of a limb where the affected area of skin is exposed to frequent stimulation. Whilst complete loss of sensibility in the superficial radial area is not disabling in everyday life and therefore plays little part in determining the use made of the injured limb a minor degree of abnormality in the index finger of the dominant hand may enforce a change of occupation For example a bank clerk who had made a recovery to grade M4 S4 after injuries to the right median and ulnar nerves was unable to work as a cashier He was able to type at a normal speed and had no difficulty in handling coins, but could not count notes accurately and rapidly The only objective abnormality found was a limen of 0·4 cm for two-point discrimination on the right index finger as against 0·2 cm. on the left. Thus when making an assessment of sensory recovery it is insufficient to determine the response to touch or pin prick unfortunately it is not always recognized that qualitative abnormalities of sensibility and loss of tactile discrimination are serious disabilities for highly skilled manual workers

6 Re-education after Nerve Injuries

The aim of re-education of patients with nerve injuries is to aid the restoration of function in the damaged limb and facilitate the adjustment of the individual to his disability This process is not a simple one for the patient for the clinical condition changes gradually throughout the phase of recovery The patient must be prepared to adapt himself to each new feature of the disability as it arises and the majority are also left to face some residual disability

we have much to learn of the inter relation of somatic and psychological reactions to injury Thus it is necessary to treat the question of re-education somewhat empirically Yet it is possible to investigate the restoration of independent movement and the finer grades of sensibility more exactly and to analyse some of the factors influencing functional recovery in the hope of establishing treatment on a more rational basis.

A INVESTIGATION OF RECOVERY OF INDEPENDENT MOVEMENTS

Perfect restoration of independent movements and of the finer grades of sensibility after nerve suture or the more serious type of lesion in continuity would indicate that the central nervous system had been adjusted to compensate for abnormalities in re innervation If such an adjustment were possible re-education might be able to speed the process Sperry (1945) reviewed the clinical and experimental evidence and concluded that little or no adjustment occurs. He considered that the degree of independence and precision of movement achieved was merely an index of the proportion of nerve fibres that had returned to their appropriate destinations

A series of patients with sutures of the ulnar or radial nerve was investigated at Oxford (See section on Electromyography p 286) In every case there was electromyographic evidence of confusion of re-innervation even in those cases showing clinical evidence of some restoration of independent movement. This confusion persisted throughout the period of observation which ranged from a few months up to three years A certain number of patients had achieved a high degree of independence of lateral movement of the index finger after suture of the ulnar nerve, but the extensor indicis was partly responsible for this effect. After radial nerve suture independent extension of the thumb or index finger was sometimes simulated by learning to flex the remaining digits. On the other hand, in cases of axonotmesis there was no sign of independent movement in the early stages of recovery but in a matter of weeks or a few months restoration was achieved In the lower limb recovery after suture and the more serious lesions in continuity of the main trunk of the sciatic nerve is associated with misdirection of fibres belonging to its two components There may be considerable inco-ordination between flexors and extensors and between invertors and evertors of the foot. Confusion between invertors and evertors may be seen after lateral popliteal injuries Exercises do not seem to produce significant improvement.

An outstanding example of failure of readjustment to faulty peripheral connections is provided by the following case

A man, aged 23 sustained multiple injuries as a result of a road accident, among them a closed injury of the brachial plexus with complete paralysis from the fourth cervical to the first thoracic segment inclusive. There was some constriction of the left pupil with preservation of sweating on that side of the face. On December 13, 1945 the brachial plexus was explored the 5th, 6th and 7th cervical roots had been completely divided and the lesion was considered irreparable the inner cord was in continuity but attenuated. On July 31 1946 recovery was noted in pectoralis major and there was some recovery of sensibility in the distribution of the 5th cervical root. On January 29 1947 recovery was noted in biceps and shortly afterwards this muscle was seen to contract with deep inspiration. This phenomenon was still marked when he was last examined in 1951 and could also be observed during quiet respiration. Presumably fibres destined for the diaphragm and accessory muscles of respiration had regenerated into the biceps. Radiography of the chest on August 23 1949 showed that there was a good range of movement of the diaphragm and that strong voluntary contraction of biceps produced no effect upon the movement and position of the diaphragm. There was therefore no evidence of re-innervation of the diaphragm by any significant number of fibres normally supplying the biceps.

A good clinical result does not necessarily guarantee a good functional result. There is a real distinction between academic recovery judged in terms of return of motor and sensory function and what may be termed functional recovery which is judged in terms of the patient s ability to return to complete social and economic independence in spite of grave physical handicaps.

In attempting to plan a rational course of re-education we are faced with anatomical physiological and psychological problems some of which must be considered briefly In all but the most favourable types of injury there are persistent peripheral abnormalities Weakness loss of independent movement and the finer grades of sensibility are inevitable unless some compensatory adjustments to these faulty connections can be made by the central nervous system. All the available evidence seems to show that no such adjustment is possible in man Furthermore, there are reasons to believe that during denervation changes occur in the spinal cord and possibly at higher levels. Romanes (1946) found significant changes in the appropriate segments of the spinal cord in the young rat after denervation or amputation of limbs In his review of previous work he shows that similar changes have been reported in man Inevitably there is little opportunity for such investigations and the extent and reversibility of the changes are unknown

As we are not yet certain of the patterns of neuromuscular activity associated with skilled and unskilled movements in the normal individual it is difficult and perhaps impossible to get a clear conception of the adjustments which must take place in such patterns when a mixed nerve is injured An injury *causing degeneration results not only in paralysis of a group of muscles*, but also in the complete cessation of the normal stream of afferent impulses from the affected cutaneous and proprioceptive end-organs to the central nervous system. In the light of Walshe s (1947) discussion of the profound influence exerted by afferent impulses on the function of the pyramidal tract, this loss cannot be ignored This author suggests that a voluntary movement is moulded throughout its course by the constant stream of afferent impulses which are influencing the motor cortex. In addition to these integrated afferent impulses, mental processes such as judgment and timing play an intimate part in the proper performance of voluntary movements.

The rapid acquisition of trick movements is evidence of modification of the pattern of movement in the remaining normal muscles The speed with which they are acquired has been observed by many including Braithwaite, Channell Moore and Whillis (1948) It is possible that these 'tricks may represent some hitherto subordinate aspect of normal function which is brought into prominence by the suppression of function in the paralysed muscles. For example, it may only be a matter of days before a patient with complete division of median and ulnar nerves above the level of the elbow learns to flex the fingers passively by extension of the wrist. That he should learn to do this is perhaps not as surprising as it seems at first sight, for flexion of the fingers in grasping is normally associated with synergic contraction of the extensors and flexors of the wrist. Paralysis of all the flexors leaves the extensors unopposed the range of extension then exceeds the normal and passive flexion of the fingers takes place. Once learned some of these trick movements are difficult to eradicate even after recovery of the paralysed muscles has occurred.

Not only are we ignorant of many of the mechanisms underlying these patterns of neuro-muscular activity but also we do not fully understand the anatomical and physiological factors entailed in the process of education, and

is no reason to alter the conclusion reached in the report to the Medical Research Council (1920) where it was stated the degree of specialization of function in different nerves and in separate muscles supplied by the same nerve has a prominent bearing on recovery"

D USE OF SPLINTS IN RE EDUCATION

Whilst there are no means of compensating for loss of cutaneous sensibility theoretically it might be possible to minimize the disturbance in the patterns of proprioceptive function both in the normal and the recovering muscles, by the use of active splinting. The correct length of the paralysed muscles is maintained and undue shortening of active muscles is prevented moreover activity is not hampered and the muscles are able to contract against an elastic or spring resistance. Such resistance cannot reproduce the action of normally innervated antagonists, but although the hypothesis lacks proof at present it is not unreasonable to suppose that conditions approach more nearly to the normal state. Another unproven but reasonable hypothesis was put forward by Capener (1948) he considers that the use of such splints should hasten the re-establishment of proprioceptive functions once the paralysed muscles become re innervated

There is evidence that active splinting aids the relearning of skilled movements but the part played by the splints cannot be analysed precisely Activity of the injured limb is maintained, undesirable trick movements are prevented and throughout the stage of paralysis the patient is able to see the passive reproduction of movements normally carried out by the inactive muscles That these factors are probably important is suggested by the patient who stated that "there is no chance of forgetting how to use the hand"

E PSYCHOLOGICAL FACTORS AND SOCIAL AND OCCUPATIONAL ADJUSTMENT

The wide variation in functional results amongst patients with similar disabilities suggests that psychological factors might be involved An exploratory investigation was therefore carried out by D Russell Davis (1949) working as a part time member of the scientific staff of the Medical Research Council. The aims of the investigation were to throw light upon two allied problems the so-called *psychological* factors affecting recovery from physical illness and the effects of physical disability upon social and occupational adjustment

Material A representative sample of 82 patients was taken from those attending a systematic follow up clinic, where 90 per cent of those sent for attended All had been treated at recognized centres during the war In addition information was obtained from a further 32 patients selected for interview with Davis on account of special points of interest. Ten children treated and followed up at the Oxford centre were interviewed and examined later The disabilities ranged from a slight clumsiness in manipulation, noticed only in cold weather to a virtually useless limb

Methods The view was adopted that the aim of treatment of peripheral nerve injuries is to restore the patient to a full useful and satisfactory mode of life The following questions were therefore posed "What degree of success has been achieved?" and "With what factors is lack of success associated?"

Success of treatment was judged on two standards the grade of employment of the patient at the time of interview and the occurrence of nervous symptoms Other factors which were considered were the degree of disability the patient s

Results in children On the whole a higher grade of recovery is achieved in children than in adults with comparable lesions It has been suggested that this difference is due to less rigidly established pathways in the central nervous system. This would allow the formation of new central nervous pathways and adjustments could therefore be made to accommodate the peripheral abnormalities On the other hand, these more favourable results might be interpreted as evidence that the process of regeneration is more active in children and it is perhaps significant that children are physically more active than adults. However even among children complete recovery has yet to be seen after sutures of the ulnar or median nerves.

B EFFECTS OF ELECTROTHERAPY AND EXERCISES ON INDEPENDENT MOVEMENT

Jackson (1945) had the impression that the degree of recovery of independent movement tended to be higher in patients who had received regular galvanic exercise for the paralysed intrinsic muscles of the hand. The part played by electrotherapy cannot be assessed accurately but it may be significant that the patients have sometimes stated that treatment was beneficial because it gives the idea of moving and because "it helped to set one about doing the movement for oneself" There is also some evidence that those employed in skilled trades or having pastimes and hobbies that demand manual dexterity tend to develop a measure of independent movement.

C RECOVERY OF SENSORY DISCRIMINATION AND LOCALIZATION

The problems of sensory re adjustment are great, for abnormalities of threshold quality and discrimination are concerned Here again children tend to achieve higher grades of recovery but there are too many factors involved to invoke the plasticity of the nervous system. Although it is possible for patients to teach themselves to localize stimuli up to a point it does not appear to be common During the course of 1 274 examinations in one year only one patient volunteered the information that he had taught himself to remember that sensations apparently arising in the tip of the 5th digit were in fact due to stimulation of a particular spot on the palm of the hand There had been a definite conscious effort to memorize this fact. Others may well have made some such adjustment Another interesting case is that of a man of 21 who sustained a gunshot wound of the arm which severed the brachial artery and the median and ulnar nerves Scar tissue was dense and extensive and when the wound was explored six months later the proximal stump of the ulnar nerve was inadvertently sutured to the distal stump of the median Regeneration proceeded with return of voluntary power in the median muscles and recovery of sensibility which was referred at first to the ulnar area later to the median and ulnar areas and occasionally to the median area alone. Localization was accurate to within 1 cm. in some areas (it was not stated whether these lay in the boundary zones) Two years after injury the proximal stump of the median nerve was sutured to the distal stump of the ulnar and one year later abnormal pain sensibility had returned to the hypothenar eminence but was referred solely to the median area

On the whole there is no definite evidence to suggest the existence of compensatory adjustments in the central nervous system to faulty peripheral connections However there is an indication that constant usage may lead to greater manual dexterity even in the presence of such abnormalities. There

When the age of the patients was taken into consideration it was found that an undue proportion of the youngest group (born between 1920–26) was in unsatisfactory employment with a poor relative functional recovery This was somewhat surprising since it is generally accepted that other things being equal the younger the patient the better the expectations of academic and functional recovery after nerve injury Further enquiry showed that most of these younger patients had not found stable or skilled employment before being called up for military service, and had no particular trade to which they could return despite their disability They had probably not learned to accept the responsibilities of independence and hardly any of those who returned to their parents were properly employed The older men not only had responsibilities, but also an occupation whose demands and standards were well known to them

In the modern view active use of the injured limb should encourage academic and functional recovery The data obtained from interviews and examinations were used to test this hypothesis An exercise rating was made in the case of arm injuries, which was based on the degree to which an occupation obliged the patient to exercise the injured limb The correlation of this rating with relative academic recovery was just significant statistically (T = 0·237) the correlation was closer when other activities such as sports and pastimes were also taken into consideration (T then being 0 375) A much closer correlation (T = 0·608) was found with relative functional recovery when occupational exercise alone was considered and closer still (0·692) when sports and pastimes were included

As the dominant arm tends to be exercised more than the other it is probable that ratings of recovery would be more favourable in the respect of the former This was borne out in the case of relative functional recovery but in the case of relative academic recovery the tendency was not significant, although it was in the right direction This suggests that recovery was better because the tendency to use the limb was stronger However it is not necessary to accept this hypothesis, for it might be argued that the tendency to exercise the limb was evidence of good recovery for other reasons. This alternative is weakened by the fact that correlation between exercise of all kinds and the degree of disability was small and insignificant. On the other hand, the relative functional recovery tended to be good in those with satisfactory employment, although the correlation between relative academic recovery and the class of employment was insignificant.

Incentives to recovery were found to be significant for example, an art student who had severe injuries to both hands was determined to return to painting and has succeeded in doing so Many of the patients reported that they had become discouraged, uncertain and anxious about their future. The activities prescribed during the prolonged stay in certain centres had seemed aimless and it had required considerable effort to persist in them. Confidence was only slowly regained on return to work, and in some cases had not been fully restored four or five years after injury This lack of confidence was a marked feature in those who had a long period of waiting before admission to a training centre, or in those who had suffered from unemployment or had only casual employment. The worst cases were fortunately few and were not amongst those investigated by Davis these men had waited months for a place in a training centre and had either been turned down after a few weeks or had been through the training only to find that no employment could be found in that trade They then drifted to unsatisfactory and unskilled work.

age, the degree to which the limb was exercised during recovery the incentives to recovery hysteria and concurrent illness On the basis of the clinical records and follow up examinations, the following assessments were made

*Relative academic recovery** (+3 to −3) The question was asked "How does the academic recovery of this limb judged in terms of motor and sensory function compare with that which would have been expected on purely surgical considerations?" In making this assessment many factors had to be taken into consideration, such as the nature and level of the injury in the nerve trunk the presence of associated vascular and bony injuries, damage to muscle and skin, and the degree of joint stiffness Where the nerves had been repaired it was also necessary to consider the delay before operation the length of the gap between the proximal and distal stumps, the appearance of the sutured surfaces and the state of the suture line itself suture materials and the rapidity of post operative stretching of the nerve It is, therefore, clear that this assessment was subject to considerable personal error however an attempt was made to minimize this by making two assessments the first at the time of examination of the patient and the second some weeks later when no reference was made to the first assessment. It was found that there was reasonable agreement between the two If the recovery came up to expectations, the relative academic recovery was graded as 0 Grades +1 2, or 3 indicated unexpectedly satisfactory recovery and grades −1 2 or 3 indicated failure to reach the expectations in the particular case.

Relative functional recovery (+3 to −3) The question was asked "How does the functional recovery compare with what would have been expected on purely surgical considerations?" Functional recovery was judged by the use made of the injured limb by the patient.

Degree of disability (*mild or severe*) The degree to which the injury was still a handicap was estimated without reference to any particular occupation and was based mainly upon the academic recovery

The ratings cannot be regarded as absolute and like the patient s statements, were subject to error Nevertheless, the findings were of interest.

Results of psychological investigation. Fifty three per cent of the representative sample of male patients had returned to employment of the same grade as they had held before injury although not always in the same trade or profession A quarter were satisfactorily employed in a lower grade and one fifth had unsatisfactory employment One fifth of the patients complained of nervous symptoms mostly those of an anxiety state, some of these symptoms were mild Nervous symptoms were present in 50 per cent of those in the lowest grade of employment and only in 13 per cent of those in the highest Clearly unsatisfactory employment and nervous symptoms tend to be associated, a vicious circle probably being set up Where more suitable employment was found for some of these patients symptoms tended to subside without special treatment.

Unsatisfactory employment could not be wholly attributed to the severity of the disabilities. A large proportion of those with the more severe residual disabilities had changed their employment to one that was satisfactory although of a slightly lower grade. The disabilities of those in unsatisfactory employment were, on the whole no greater than those in the two groups of patients who had returned to satisfactory work

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* By *academic recovery* is meant the neurological assessment of recovery, in terms of an agreed grading (see p. 355). This grading is not necessarily related to the ultimate functional usefulness of the affected part.

factors appears to be the necessity for constant usage at work in pastimes and sport.

Surgical intervention for repair of damaged nerves or reconstruction is but an incident in the treatment, for the ultimate success of all therapeutic measures lies, to a large extent, in the hands of the patient. Once this fact was appreciated the willing co-operation of most of them was remarkable.

The best results were found in those patients who from the time of injury had no doubt of the employment to which they would be able to return Most of them decided upon the object of treatment and were determined to reach it. They not only had a reason for co-operation and showed persistence in carrying out active exercises and other forms of treatment, but were able to estimate progress in terms of a standard which they understood and valued

Neurotic manifestations had been of no practical significance in delaying recovery it was found in only one patient out of the main sample (75) and one in the additional group (32) In no patient was the desire to retain a certain pension thought to be a factor appreciably affecting recovery Several patients were dissatisfied with their treatment by the pensions authorities, largely on account of ignorance of the basis of assessment and of the conditions under which appliances and footwear are supplied The majority shared this ignorance, and were sometimes reluctant to discuss their activities, and in particular their participation in sport, for fear of suffering an undeserved reduction in pension

The relative functional recovery of the peripheral nerve injury was poor in every one of the five patients suffering from concurrent illness

F CONCLUSIONS

Delay and uncertainty about return to satisfactory employment are demoralizing and cause much unhappiness. Some of this distress is avoidable, for it is usually possible to give a fairly sound prognosis in these cases At least the best and the worst outlook and the possibility of reconstructive surgery can be discussed. It appears that in some centres insufficient attention has been paid to enlisting the patients active co-operation in treatment and re-education From this investigation it is clear that self reliance and independence should be cultivated from the time of admission to hospital, not only for the sake of raising morale, but also to get the best possible functional result. The patients need encouragement to do as much as possible for themselves, and at this stage the example of other disabled patients is particularly valuable. Once it is realized that their problems receive a practical and sympathetic understanding, and that they themselves play a large part in their treatment few patients seek indulgences. Should training be necessary arrangements should be made by the hospital authorities in collaboration with the patient and the Disablement Rehabilitation Officer of his own locality Given this reassurance, there is an excellent incentive to continue with treatment and occupational therapy during the period of waiting for admission to a training centre. However if possible, it is more desirable for the patient to seek suitable employment amongst normal persons at the earliest opportunity The success of such measures is demonstrated by the experiments reported by Napier Barron Gregory and Thompson (1947) and by Plewes Barron Thompson and Newell (1948) Jobs should be selected, and even if some adjustment of tools or machinery is necessary there is no artificiality about the occupation Repetitive movements of graded skill in good lighting and heating conditions are particularly valuable in re-education the patient can measure his progress by the output and quality of his work and he has the added satisfaction of being self-supporting.

Splints, active and passive exercises and physiotherapy play an important part in re-education by preventing or minimizing the adverse effects of denervation and by maintaining mobility of the part but one of the most significant

and other physical handicaps environment, and psychological factors profoundly influence the way in which a patient uses the injured limb (Davis, 1949) One patient with a complete sciatic nerve injury may have less disability than another who has considerable return of motor power and sensibility The assessment of recovery must therefore be made primarily on a neurological basis, the principal guides being restoration of sensibility and the return of muscle power and control Neurological recovery will usually improve the function of the limb and unless disabled in some of the ways just mentioned patients with better neurological recovery will have better function

In defining the neurological criteria vagueness must be avoided It does not matter whether the grades are called good fair poor cured improved unchanged or M0 M1 M2 so long as these terms correspond to grades of recovery that are clearly defined. Motor and sensory recovery must be assessed separately and the full range from total paralysis to complete recovery should be covered by grades which represent recognizable steps in recovery

In a memorandum addressed to the Nerve Injuries Committee, Highet suggested a method of grading which fulfils these requirements and which is the foundation of this analysis His criteria were strict and although some modification has since been found necessary for certain nerves his tables of grading are given below in their original form

I Sensory Recovery

Stage 0—absence of sensibility in the autonomous zone of the nerve
Stage 1—recovery of deep cutaneous pain sensibility within the autonomous zone
Stage 2—return of some degree of superficial pain and tactile sensibility within the autonomous zone
Stage 3—return of superficial pain and tactile sensibility throughout the autonomous zone with the disappearance of over response
Stage 4—return of sensibility as in Stage 3 with the addition that there is recovery of two-point discrimination within the autonomous zone.

II Motor Recovery

Stage 0—no contraction
Stage 1—return of perceptible contraction in the proximal muscles
Stage 2—return of perceptible contraction in both proximal and distal muscles
Stage 3—return of function in both proximal and distal muscles to such an extent that all important muscles are of sufficient power to act against resistance.
Stage 4—return of function as in Stage 3 with the addition that all synergic and isolated movements are possible
Stage 5—complete recovery

The stages give a good picture of the progress of recovery It has already been mentioned that some deviation from, or elaboration of this system has been found necessary mainly by including subheadings to indicate further important stages. For example, for the median nerve M1 indicates recovery in the long flexor muscles After high suture there are many cases that do not

Centres and a small group from another hospital where similar methods of recording and grading were in use. Certain cases were excluded

1 Nerve sutures performed after December 31 1945 The reason was that the minimum period of post-operative observation was three years, and for the purpose of this analysis, the final reviews were made at the end of 1948

2 If the period of observation was less than one year A number of sutures performed before 1945 were not followed adequately Those observed for less than one year were excluded because the information they yielded concerning recovery was of necessity incomplete. It might be thought that in some cases failure to attend for examination was due either to the patients being well satisfied with the recovery they had made or disgruntled because of its absence. The exclusion of these cases might then upset the balance of the remainder However neither factor would be strongly operative within the short period of one year after suture, and the omission of the entire group simplifies the analysis without impairing its statistical value.

3 Those with inadequate records which did not provide information about the site of suture, the delay before repair and the length of nerve resection

In order to obtain a valid comparison of the results in one group with those in another it was necessary to assess recovery at approximately equal intervals after nerve suture For this reason the assessments used in this analysis are those made at approximately 12, 24 36 and 60 months after operation If any improvement occurred between three and five years it was noted but if the patient was not seen after three years, the recovery recorded at this time was assumed to be that which would be present at five years

Lapse rate In spite of all attempts to keep in touch with patients after operation a certain number disappeared from view or refused to attend for re-examination. As mentioned above, those followed for less than one year were excluded altogether but those followed for more than twelve months were included even though they were not seen later Table 72 shows the lapse rate at 24 and 36 months Seventy-seven per cent of the patients seen one year after operation were seen again at the end of three years The lapse rate of nearly a quarter of the cases introduces a potential element of inaccuracy into the summary of results. If those cases which lapsed at two or three years are excluded and only the results based on cases actually observed are presented the accuracy of the figures depends on the assumption that the proportion of recoveries in the lapsed cases is the same as that in the cases observed. This assumption is not unwarranted Although some patients may have discharged themselves because they thought they were cured, and others because they believed themselves incurable, in general it is unlikely that the quality of recovery determined their defection. In most cases it was known that social financial, domestic or business considerations were chiefly responsible for non-attendance some patients went abroad others died If this assumption is inaccurate it errs on the side of an under-estimate of the proportion of recoveries in other words, there was a greater proportion of recoveries amongst the lapsed cases than among those observed It will be noted that the lapse rate for patients suffering from radial nerve lesions was nearly twice as great as that for any other group Radial paralysis is very disabling no victim of it who had passed through a Nerve Injuries Centre would be ignorant of the possibility of tendon transplantation if the result of nerve suture was disappointing. Therefore, there is a strong probability that in this group at any

rate some patients defaulted because they were well satisfied rather than because they were disappointed.

The only alternative to analysis in this way was to present the two possible extremes of recovery the first assuming that *all* lapsed cases failed to recover and the second assuming that *all* lapsed cases recovered satisfactorily Such a method of presentation was seriously considered but was discarded as giving a confusing picture. Although the method used has some inherent defect (probably an under-estimation of the proportion of recoveries) the problem of lapsed cases has been dealt with by excluding them from the analysis as they arose.

TABLE 72

Follow-up of nerve suture in years

	Follow-up (years)			Lapse rate	
	1	2	3	Proportion	%
Ulnar	499	482	382	117/499	23 5
Median	351	320	288	63/351	17·9
Radial	195	157	113	82/195	42 0
Medial popliteal	132	146	122	10/132	7·6
Lateral popliteal	264	250	203	61/264	23 0
Total	1441	1355	1108	333/1441	23 0

B METHOD OF ANALYSIS

Complete motor and sensory recovery does not occur after nerve suture After allowance has been made for right or left handedness of the patient, there is always some slight difference to be detected by the patient or by the observer The nearest approach to normality was seen in a few cases of radial nerve suture the strength of the extensors of the fingers was excellent and their independent movements were good—yet, although on examination of the affected hand alone it would be considered normal in comparison with the other hand there was a slight but distinct inferiority Similarly after suture of

the median nerve in young children there were a few instances in which power and control of muscles were excellent and tactile localization and discrimination very good but sensibility was not absolutely normal Since so few patients even approach the normal following nerve suture the criterion of perfect or almost perfect recovery was not of much help and these almost perfect recoveries were grouped with others in a high grade of recovery Similarly there was seldom no evidence whatever of recovery for the same reason those with complete paralysis are usually grouped with those showing recovery which was so slight as to be valueless

It was found necessary to select a useful grade of recovery' for each nerve that is, the grade that repays performance of suture. For example, after suture of the ulnar nerve at the wrist a return of voluntary power in the hypothenar muscles alone is of no value to the patient and should not be considered a useful degree of recovery However if regeneration leads to activity in all the dorsal interossei the function of the hand is distinctly improved and the repair can be considered worthwhile The useful grade of recovery according to the nerve concerned varies for the ulnar nerve it is M2+ for the radial M3 and for the medial popliteal M1(4) Reference will be made to these particular grades in the course of the analysis

The following have been adopted as definitions of the level of suture

Nerve	High	Intermediate	Low
Ulnar	Above branches to flexor carpi ulnaris	Between branches to flexor carpi ulnaris and flexor digitorum profundus	Below branches to flexor digitorum profundus
Median	Above branches to pronator teres	Between branches to pronator teres and flexor pollicis longus	Below branch to flexor pollicis longus
Radial	Above mid-point of spiral groove	Between mid-point of spiral groove and terminal branching	Posterior interosseous nerve
Sciatic	In buttock or more than 30 cm. above lateral femoral condyle	In thigh or 10–30 cm. above lateral femoral condyle	Popliteal fossa less than 10 cm. above lateral femoral condyle

2. Results

(i) *Ulnar Nerve*

After suture of the ulnar nerve motor recovery is more important than sensory Table 73 shows the return of motor function after ulnar nerve suture M2+ indicates return of power in all the interossei although not to the degree of strong mass action—which would be represented by M3 M2+ is considered to be a useful grade (Fig. 247) M2, the next lower grade is not considered satisfactory since it represents merely some action in the hypothenar muscles without any definite interosseous recovery

Only 5 per cent of patients recovered some independent action in the intrinsic muscles of the hand (M4) and those requiring finely controlled movements of the fingers for their occupations would be disappointed However the prospects after suture were not bad under all conditions there was an even chance of useful recovery and in certain circumstances—a low site of suture, a short resection and short delay—78 5 per cent made a useful recovery and 16 per cent regained independent movements of the fingers (Table 83)

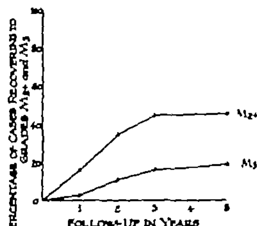


FIG. 247 Ulnar nerve motor recovery in all 384 cases.

Sensory recovery to grade S2+ corresponds to return of touch and pain sensibility to the tips of the fingers but with persistent over reaction. In the next higher grade, S3 there is no longer any over reaction—a considerable improvement. S2+ is judged to be a useful grade of recovery and was reached in 46 per cent of cases (Table 74) Thirty per cent reached grade S3

TABLE 73

Ulnar nerve suture motor recovery

Grade of recovery	Follow-up in years 1			2			3			5		
	No.	%	C%	No.	%	C%	No.	%	C%	No.	%	C%
M4	2	0·4	0·4	12	2·5	2·5	17	4·5	4·5	19	4·9	4·9
M3	7	1·4	2·8	41	8·5	11·0	45	11·8	16·3	55	14·3	19·2
M2+	66	13·3	16·1	117	24·3	35·3	110	28·8	45·1	104	27·1	46·3
M2	125	25·0	41·1	254	52·7	88·0	186	48·6	93·7	186	48·4	94·7
M1+	299	59·9	100·0	58	12·0	100·0	24	6·3	100·0	20	5·3	100·0
Total	499			482			382			384		

C% = Cumulative percentage throughout tables.

TABLE 74

Ulnar nerve suture sensory recovery

Grade of recovery	Follow-up in years 1			2			3			5		
	No	%	C%	No	%	C%	No.	%	C%	No		C%
S3+	2	0·4	0·4	4	0·8	0·8	6	1·5	1·5	10	2·6	2·6
S3	28	5·4	5·8	94	19·5	26·7	98	25·0	26·5	110	28·2	30·8
S2+	43	8·4	13·2	68	14·1	34·8	66	16·8	43·3	59	15·2	46·0
S2	447	85·8	100·0	316	65·6	100·0	222	56·7	100·0	211	54·0	100·0
Total	515			483			392			390		

When delay and resection were short and the suture was low 50 per cent of patients recovered to grade S3 (Table 92 p 379)

(ii) *Median Nerve*

Both motor and sensory recovery are important. M3 indicates the return of strong palmar abduction of the thumb as well as recovery in the long flexors if they were paralysed Thirty two per cent of all cases reached this grade (Table 75 Fig. 248) An important distinction concerning motor recovery must be drawn here between the high and low sutures After a low suture motor recovery can hardly be said to be worth while unless there is power of wide abduction of the thumb—a mere flicker of movement in the thenar muscles is useless. However after a high suture return of power in the long flexor muscles is worth while even if there is little or no return of function in the thenar muscles and the corresponding grade of recovery is M1+ Table 76 shows motor recovery after high sutures of the median nerve although only 19 per cent reached grade M3 almost 90 per cent reached a useful grade of recovery (Fig. 249)

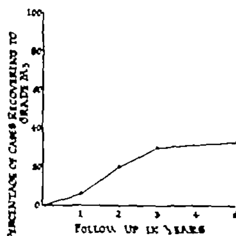


FIG. 248 Median nerve motor recovery in all 290 cases.

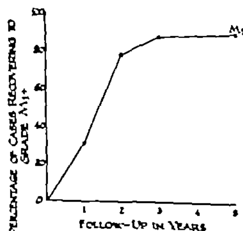


FIG 249 Median nerve high sutures motor recovery in 51 cases.

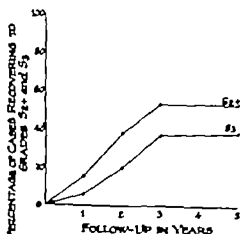


FIG. 250 Median nerve sensory in all 278 cases.

The grading of sensory recovery is similar to that for the ulnar nerve S2+ being regarded as a worthwhile grade Table 77 shows that 53 per cent reached this grade and 38 per cent reached the higher grade of S3 in which over reaction had disappeared (Fig. 250) When the analysis is restricted to low early sutures with a short resection (Table 94) just over one half of the cases (52 per cent) reached S3 and two-thirds (68 per cent) made useful recoveries.

TABLE 75

Median nerve suture motor recovery

Grade of recovery	Follow-up in years											
	1			2			3			5		
	No.	%	C%	No.	%	C%	No.	%	C%	No.	%	C%
M4	7	2.0	2.0	31	9.7	9.7	49	17.6	17.0	54	18.6	18.6
M3	16	4.6	6.6	33	10.0	20.0	39	13.6	30.6	41	14.1	32.7
M2	69	19.0	26.1	109	34.1	54.1	92	31.9	62.5	89	30.7	63.4
M1+	187	53.3	79.6	125	39.2	93.3	96	33.3	95.8	95	32.8	96.2
M1	72	20.4	100.0	22	6.7	100.0	12	4.2	100.0	11	3.8	100.0
Total	351			320			288			290		

TABLE 76

Median nerve high suture motor recovery

Grade of recovery	Follow-up in years											
	1			2			3			5		
	No.	%	C%	No.	%	C%	No.	%	C%	No.	%	C%
M4				1	1.0	1.0	6	6.4	6.4	6	6.4	6.4
M3	2	1.9	1.9	4	4.0	5.0	8	8.5	14.9	12	12.8	19
M2	4	3.8	5.7	41	41.0	46.0	43	45.7	60.6	39	41.4	60.6
M1+	27	25.7	31.4	32	32.0	78.0	25	26.6	87.2	26	27.7	88.3
M1	72	68.6	100.0	22	22.0	100.0	12	12.8	100.0	11	11.7	100.0
Total	105			100			94			94		

TABLE 77

Median nerve suture sensory recovery

Grade of recovery	Follow-up in years											
	1			2			3			5		
	No	%	C%	No	%	C%	No.	%	C%	No.	%	C%
S3	1	0.3	0.3	4	1.2	1.2	18	6.7	6.7	24	8.6	8.6
S3	20	5.7	6.0	62	19.2	20.4	82	30.4	37.1	82	29.5	38.1
S2	34	9.7	15.7	58	18.0	38.4	44	16.4	53.5	42	15.2	53.3
S2	295	84.3	100.0	199	61.6	100.0	125	46.5	100.0	130	46.7	100.0
Total	350			323			269			278		

(iii) *Radial Nerve*

Sensory recovery is unimportant after suture of the radial nerve and will be disregarded M2 corresponds to recovery in the proximal muscles but no worth while recovery in the distal muscles extending the index and thumb this degree of recovery is worth having if there is no alternative But if there are sufficient muscles available for transplantation the next grade (M3) must be reached to justify the suture Eighty nine per cent of cases reached grade M2 and 61 per cent M3 The next higher grade, M4 which indicates some return of finer control and co-ordination of the extensors of the finger and thumb was reached after 36 per cent of sutures (Table 78 Fig 251)

TABLE 78

Radial nerve suture motor recovery

Grade of recovery	Follow-up in years											
	1			2			3			4		
	No.	%	C%	No.	%	C%	No.	%	C	No.	%	C%
M4	9	4 6	4 6	31	19 8	19 8	41	36 2	36 2	42	36 9	36 9
M3	31	15 9	20 5	45	28 7	48 5	28	24 8	61 0	28	24 6	61 5
M2	86	44 1	64 6	57	36 2	84 7	31	27 5	88 5	32	28 0	89 5
M1	69	35-4	100 0	24	15-3	100 0	13	11 5	100 0	12	10-5	100 0
Total	195			157			113			114		

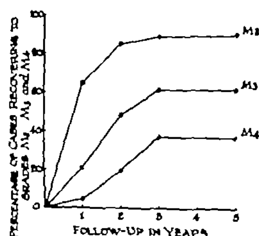


FIG 251 Radial nerve motor recovery in all 114 cases.

Even when the suture was performed early and the resection was short, not more than 71 per cent of sutures at the intermediate level reached M3 but more than half recovered to grade M4 (Table 95 p 380)

(iv) *Sciatic Nerve*

The sciatic nerve is considered in terms of its two components thus a high suture of the nerve is regarded as a suture of each component at that level

(*a*) *Medial popliteal nerve*

The return of strong action in the calf muscle (against gravity and resistance) is a useful grade of motor recovery Table 79 (Fig. 252) shows that 56 per cent of medial popliteal sutures were followed by recovery to this grade M1(4)

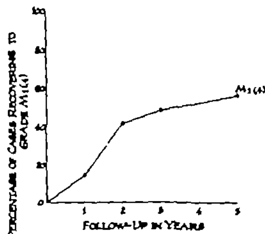


FIG. 252. Medial popliteal nerve motor recovery in all 126 cases.

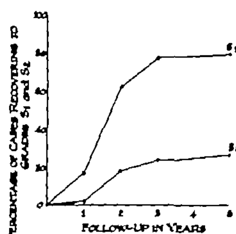


FIG. 253 Medial popliteal nerve sensory recovery in all 118 cases.

Return of power to the flexors of the toes is so rare as to be negligible. Of 22 early sutures in the mid thigh in which the resection was short, 73 per cent reached M1(4) (Table 96)

Assessment of tactile sensibility in the sole of the foot is difficult chiefly on account of the thickness of the skin Table 80 shows that only 27 per cent of patients gave any evidence of tactile sensibility (S2) whereas 80·5 per cent showed some response to pin prick (Fig. 253)

TABLE 79

Medial popliteal nerve suture motor recovery

Grade of recovery	Follow-up in years											
	1			2			3			5		
	No.	%	C%	No.	%	C%	No.	%	C%	No.	%	C%
M1 (4+)	4	3·3	3·3	25	17·1	17·1	30	24·6	24·6	32	25·4	25·4
M1 (4)	14	10·6	13·9	35	24·0	41·1	29	23·8	48·4	9	31·0	56·4
M1 (3)	28	21·1	35·0	29	19·9	61·0	26	21·3	69·7	23	18·2	74·6
M1 (2)	86	65·0	100·0	57	39·0	100·0	37	30·3	100·0	32	25·4	100·0
Total	132			146			122			126		

TABLE 80

Medial popliteal nerve suture sensory recovery

Grade of recovery	Follow-up in years											
	1			2			3			5		
	No.	%	C%	No.	%	C%	No.	%	C%	No.	%	C%
S3				3	2·4	2·4	5	4·2	4·2	8	6·8	6·8
S2 –				6	4·1	6·5	2	1·7	5·9	2	1·7	8·5
S2	3	1·9	1·9	18	12·2	18·7	21	17·8	23·7	22	18·6	27·1
S1	24	15·3	17·2	63	42·6	61·3	64	54·2	77·9	63	53·4	80·5
S0	130	82·8	100·0	57	38·7	100·0	26	22·1	100·0	23	19·5	100·0
Total	157			147			118			118		

(b) *Lateral popliteal nerve*

After repair of the lateral popliteal nerve there must be recovery of dorsi-
xion of the foot against gravity M1 (3) before the result can be regarded as
tisfactory Thirty-six per cent of cases reached this grade only 13 per cent
ere able to lift the foot against gravity and resistance M1 (4) (Table 81
g. 254). When the level of suture was low and the delay and the resection
ere short, 59 per cent made a useful recovery and 32 per cent reached grade
1 (4) (Table 98)

TABLE 81

Lateral popliteal nerve suture motor recovery

Grade of recovery	Follow-up in years											
	1			2			3			5		
	No.		C%	No.		C%	No.	%	C%	No.	%	C%
M1 (4)	2	0·8	0·8	20	8·0	8·0	20	9·9	9·9	28	13·6	13·6
M1 (3)	10	3·8	4·6	41	16·4	24·4	46	22·7	32·6	46	22·5	36·1
M1 (2)	30	11·3	15·9	43	17·2	41·6	37	18·2	50·8	33	16·1	52·2
M1 (1)	222	84·1	100·0	146	58·4	100·0	100	49·2	100·0	98	47·8	100·0
Total	264			250			203			205		

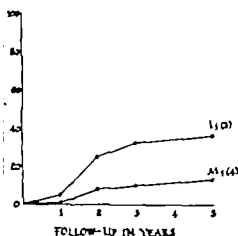


Fig. 254 Lateral popliteal nerve motor recovery in all 205 cases.

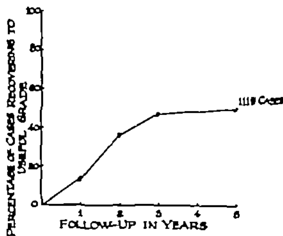


Fig. 255 All nerves motor recovery to useful grade.

(c) *Amputations for sciatic palsy*

There were twelve amputations following suture of the sciatic nerve. Three
f these patients had some sensory recovery and six had regained power in the
alf muscle In only five patients was there no evidence of regeneration one of
hese suffered amputation seven months after suture and three others shortly
fter twelve months, at a time when there were still prospects of recovery

The chief indication for the operation was deformity of the foot and ulcera
on on the sole. Amputation was performed for poor function of the limb
nd not primarily for poor neurological recovery

An idea of the relation between neurological recovery and function was
btained from a series of 107 sciatic nerve sutures. Function of the limb was
raded as follows

POOR	Presence of ulcers severely restricting activity Inability to wall more than half a mile.
FAIR	Ulcers, if present, small and not incapacitating. Inability to walk more than one mile. Sedentary work *possible* No continuous severe pain
GOOD	No ulcers or more than light pain. Ability to walk more than one mile. Ability to carry out work necessitating a fair amount of walking or standing.
EXCELLENT	No orthopaedic apparatus required Ability to walk five miles and to run Ability to carry out work necessitating walking or standing. No time off' for at least six months because of trouble with the leg.

The proportion of patients with good function was then estimated for each grade of neurological recovery as follows

Relation of function to motor recovery

Grade of recovery	Total no	Patients with good function	
		No.	✓
M1 (5)	4	4	100 0
(4)	21	14	66·7
(3)	27	17	63 0
(2)	15	3	20 0
(1)	11	2	18 2
(0)	29	8	27 5
Total	107	48	45·0

On the whole patients with better neurological recovery had better function, but eight patients with no recovery whatever had good function of the limb Thus failure of nerve suture is no indication for amputation nor is the return *of motor power or sensibility a guarantee against deformity and ulceration,* which are the principal reasons for the operation.

Adequate care of the foot is the chief safeguard and in a case of uncomplicated division of the sciatic nerve there should never be any question of amputation whatever the quality of recovery following suture.

(v) *All Nerves*

Since motor recovery is important in all the main nerves it is desirable to give a general picture of the proportion of cases making a useful recovery The actual grading varies from one nerve to another but for each the grade *chosen was that indicative of useful recovery* Fig. 255 shows that 50 per cent of all cases of suture made a useful recovery

3 Factors Influencing Recovery

It is possible to enumerate many factors which may influence recovery after nerve suture

Age may influence the rate of regeneration of nerve fibres It is likely that the *general health* of the subject is important Fortunately these factors may be ignored in this analysis since almost all the patients were healthy young men between the ages of 18 and 30 years

The *nature of the wound* is significant A high velocity projectile damages the nerve stumps more extensively than a clean cut This factor usually determines the extent of the resection found necessary at operation Sepsis causes delay in healing of a wound and therefore increases the interval between injury and repair of the nerve.

The *level of the injury* is most significant the more proximal the lesion the poorer the prospect of recovery

Delay before repair as has been shown elsewhere is most harmful because it leads to increasingly deleterious changes in the distal stump of the nerve and in the tissues with which it is connected

The *findings at operation* influence the result. If resection is required for a lesion in continuity the operation produces only a small upset in the funicular pattern at the suture line An extensive lesion has the opposite effect it may also tempt the surgeon to resect the stumps inadequately (p 111), and there may be risk of separation or of intraneural fibrosis when post-operative stretching of the limb is carried out.

The *pre- and post-operative treatment* (see Chapter VII) greatly influences the result.

Any attempt to break down a series of some 1 000 cases into groups corresponding to each of these factors would be futile, since the numbers would be too small for reliable analysis Yet these factors cannot be discounted altogether and some solution must be sought. Although to some extent it involves begging the question for detailed consideration there must be a division of these influences into important and unimportant, or specific and general The three factors selected for analysis were site of suture, delay before suture and length of resection Of the remaining factors some act independently of the three selected, for example the skill of the surgeon or the material used for suture Because they were not related to what for the purpose of this analysis may be called the three primary factors it is reasonable to suppose that any influence they exert is spread evenly through the series. The method of suture the extent of mobilization of the nerve, post-operative therapy and psychological factors, may all be important but are as likely to affect a high suture as a low one, a late suture as an early one a long resection as a short one. Consequently they are unlikely to divert the general trend of results in one or other direction although they may to some extent mask the full influence of the primary factors and produce the exceptional and unexpected result by an accidental confluence

On the other hand there are several conditions related to the primary factors for example severe wounds (often gunshot wounds) are more likely than simple lacerations to cause delay before suture If it is found that late sutures do not recover well that is not proof either that delay of itself has retarded recovery or that preponderance of gunshot wounds among the late sutures has been the prevailing influence Has the type of wound affected recovery except by virtue of the delay in repair which it entailed? In the face of such questions some arbitrary selection of factors must be made In brief some factors were omitted from consideration because they were independent of what appeared to be the three most important others, although related to the primary factors, were left out because they were subsidiary

POOR Presence of ulcers severely restricting activity Inability more than half a mile

FAIR Ulcers if present, small and not incapacitating Inab walk more than one mile. Sedentary work possible. N tinuous severe pain

GOOD No ulcers or more than light pain. Ability to walk mo one mile. Ability to carry out work necessitating a fair r of walking or standing.

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Relation of function to motor recovery

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M1 (5)	4	4	100 0
(4)	21	14	66·7
(3)	27	17	63 0
(2)	15	3	20 0
(1)	11	2	18 2
(0)	29	8	27 5
Total	107	48	45·0

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with 23 per cent of high sutures. Yet it cannot be deduced from this table that a high level of suture is an adverse factor for the high lesion of the ulnar nerve was more frequently the result of serious injury entailing a long delay before suture and a greater gap after resection of the damaged segment

It is possible to reduce the influence of these two factors by considering only those sutures performed within six months of the injury in which the gap after resection was less than 5 cm Table 83 shows that even after making this restriction there was still a significant difference between the high and low sutures.

TABLE 83

*Ulnar nerve motor recovery in relation to site of suture**

Grade of recovery	Follow-up in years											
	1			2			3			5		
	No.	%	C%	No.	%	C%	No.	%	C%	No.	%	C%
High M4										1	2·8	8
M3					4·3	4·3	2	5·7	5·7	1	2·8	5·6
M2+	2	4·1	4·1	4	8·4	[illegible]	7	19·9	25·6	7	19·9	25·5
M2	9	18·5	22·6	20	42·6	55·3	21	60·1	85·7	22	63·1	88·6
M1+	38	77·4	100·0	21	44·7	100·0	5	14·3	100·0	4	11·4	100·0
Total	49			47			35			35		
Intermediate M4										1	2·3	2·3
M3				1	0	2·0	5	11·4	11·4	6	13·6	15·9
M2+		3·9	3·9	13	25·5	27·5	13	29·5	40·9	11	25·0	40·9
M2	16	31·4	35·3	37	72·5	100·0	26	59·1	100·0	26	59·1	100·0
M1+	33	64·7	100·0									
Total	51			51			44			44		
Low M4	2	1·4	1·4	11	8·6	8·6	15	16·1	16·1	15	16·1	16·1
M3	7	5·0	6·4	29	22·7	31·3	24	[illegible]	41·9	29	31·2	47·3
M2+	36	25·5	31·9	52	40·6	71·9	33	35·5	77·4	29	31·2	78·5
M2	53	37·6	69·5	36	[illegible]	100·0	21	22·6	100·0	20	21·5	100·0
M1+	43	30·5	100·0									
Total	141			128			93			93		

* Delay less than 6 months. Resection less than 5 cm.

Similar results were obtained in the analysis of motor recovery in the *median* (Fig. 257) and lateral popliteal nerves (Fig. 258) and in sensory recovery after medial popliteal suture (Fig. 259) (Tables 85 90 and 89)

For the remaining nerves the figures were in favour of the low suture, but the differences were not statistically significant. (Tables 84 86 87 and 88)

(ii) *Delay before Repair*

Since it has been shown that a high level of suture is an adverse factor the influence of the level of the lesion must be eliminated before the effects of

(I) *Level of Injury*

The influence of the level of injury has already been mentioned in con nexion with the median nerve, but that part of the discussion was concerne only with showing that a considerable proportion of high sutures achieved grade of recovery which was useful—though a grade of function that woul be regarded as a failure after low suture. In fact, motor recovery was more satisfactory after high suture than after low because there was a greater proportion of high sutures reaching grade M1+ than of low sutures reaching grade M3 On the other hand there was a closer approach to normal in a suture which reaches M3 than in one which reaches M1+

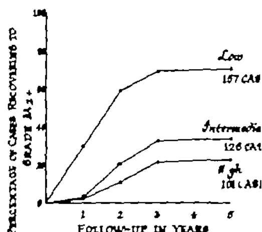


Fig 256. Ulnar nerve motor recovery in relation to site of suture.

Table 82 (Fig. 256) shows the recoveries after repair of the ulnar nerve in relation to the level of suture. Seventy-one per cent of low ulnar sutures reached grade M2+ compared

TABLE 82

Ulnar nerve motor recovery in relation to site of suture

Grade of recovery	Follow-up in years: 1			2			3			5		
	No.	%	C%	No.	%	C%	No.	%	C%	No.	%	C%
High M4										1	1	1
M3				2	1·6	1·6	4	4	4	4	4	5
M2+	3	2·3	2·3	12	10·0	11·6	18	17·8	21·8	18	17·8	22·8
M2	15	12·0	14·3	49	40·4	52·0	55	54·5	76·3	58	57·4	80·2
M1+	107	85·7	100·0	58	48·0	100·0	24	23·7	100·0	20	19·8	100·0
Total	125			121			101			101		
Intermediate M4										1	0·8	0·8
M3				4	2·7	2·7	14	11·1	11·1	17	13·5	14·3
M2+	5	3·4	3·4	26	17·8	20·5	28	22·2	33·3	25	19·8	34·1
M2	39	26·2	29·6	116	79·5	100·0	84	66·7	100·0	83	65·9	100·0
M1+	105	70·4	100·0									
Total	149			146			126			126		
Low M4	2	1·0	1·0	12	5·6	5·6	17	11·0	11·0	17	10·8	10·8
M3	7	3·1	4·1	35	16·3	21·9	27	17·4	28·4	34	21·6	32·4
M2	58	25·8	29·9	79	36·7	58·6	64	41·3	69·7	61	39·0	71·4
M2	71	31·6	61·5	89	41·4	100·0	47	30·3	100·0	45	28·6	100·0
M1	87	38·5	100·0									
Total	225			215			155			157		

with 23 per cent of high sutures. Yet it cannot be deduced from this table that a high level of suture is an adverse factor for the high lesion of the ulnar nerve was more frequently the result of serious injury entailing a long delay before suture and a greater gap after resection of the damaged segment

It is possible to reduce the influence of these two factors by considering only those sutures performed within six months of the injury in which the gap after resection was less than 5 cm. Table 83 shows that even after making this restriction there was still a significant difference between the high and low sutures

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*Ulnar nerve motor recovery in relation to site of suture**

Grade of recovery	Follow-up in years											
	1						3			5		
	No.	%	C %	No.	%	C	No.	%	C %	No.	%	C %
High M4										1	2·8	2·8
M3				2	4·3	4·3	2	5·7	5·7	1	2·8	5·6
M2+	2	4·1	4·1	4	8·4	12·7	7	19·9	25·6	7	19·9	25·3
M2	9	18·5	22·6	20	42·6	55·3	21	60·1	85·7	22	63·1	88·6
M1+	38	77·4	100·0	21	44·7	100·0	5	14·3	100·0	4	11·4	100·0
Total	49			47			35			35		
Intermediate M4										1	2·3	3
M3				1	2·0	2·0	5	11·4	11·4	6	13·6	15·9
M2+	2	3·9	3·9	13	25·5	27·5	13	29·5	40·9	11	25·0	40·9
M2	16	31·4	35·3	37	72·5	100·0	26	59·1	100·0	26	59·1	100·0
M1+	33	64·7	100·0									
Total	51			51			44			44		
Low M4	2	1·4	1·4	11	8·6	8·6	15	16·1	16·1	15	16·1	16·1
M3	7	5·0	6·4	29	22·7	31·3	24	25·8	41·9	29	31·2	47·3
M2+	36	25·5	31·9	52	40·6	71·9	33	35·5	77·4	29	31·2	78·5
M2	53	37·6	69·5	36	29·1	100·0	21	22·6	100·0	20	21·5	100·0
M1+	43	30·5	100·0									
Total	141			128			93			93		

* Delay less than 6 months. Resection less than 5 cm.

Similar results were obtained in the analysis of motor recovery in the median (Fig. 257) and lateral popliteal nerves (Fig. 258) and in sensory recovery after medial popliteal suture (Fig. 259) (Tables 85 90 and 89)

For the remaining nerves the figures were in favour of the low suture, but the differences were not statistically significant. (Tables 84 86 87 and 88)

(ii) *Delay before Repair*

Since it has been shown that a high level of suture is an adverse factor the influence of the level of the lesion must be eliminated before the effects of

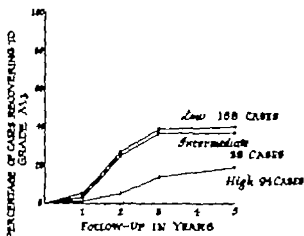


FIG 257 Median nerve motor recovery in relation to site of suture.

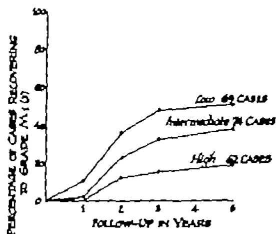


FIG. 258 Lateral popliteal nerve motor recovery in relation to site of suture.

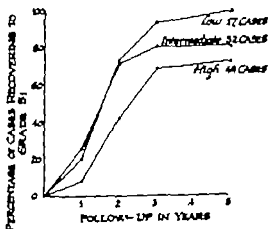


FIG. 259 Medial popliteal nerve sensory recovery in relation to site of suture.

delay can be studied. Only sutures performed at approximately the same level must be considered for example, all low or all high sutures Similarly the effect of the length of resection must be excluded by restricting the analysis to cases in which the gap after resection was less than 5 cm.

Tables 91–98 give the results in relation to delay before suture in two groups according to whether suture was performed sooner or later than six months after injury The figures clearly favour early suture but the difference between the numbers of early and later sutures making a useful recovery was significant only for sensory recovery after low median or low ulnar nerve repair Sixty-eight per cent of these early median sutures made a useful sensory recovery compared with 33 per cent of late sutures (Fig. 260) The figures for motor recovery to a useful grade

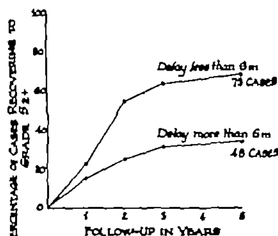


Fig 260 Median nerve sensory recovery in relation to delay before suture. (Low sutures only resection less than 5 cm.)

TABLE 84

*Ulnar nerve sensory recovery in relation to site of suture**

Grade of recovery	Follow-up in years: 1			2			3			5		
	No.	%	C%	No.	%	C%	No.	%	C%	No.	%	C%
High S3+												
S3	4	3·1	3·1	18	14·7	14·7	21	20·0	20·0	25	22·9	22·9
S2+	5	3·8	6·9	15	12·3	27·0	26	24·8	44·8	24	23·8	46·7
S2	121	93·1	100·0	89	73·0	100·0	58	55·2	100·0	56	53·3	100·0
Total	130			122			105			105		
Intermediate S3+												
S3	7	4·6	4·6	23	15·2	15·2	33	25·4	25·4	36	27·7	27·7
S2+	13	8·6	13·2	22	14·6	29·8	12	9·2	34·6	11	8·5	36·2
S2	132	86·8	100·0	106	70·2	100·0	85	65·4	100·0	83	63·8	100·0
Total	152			151			130			130		
Low S3+	2	0·9	0·9	4	1·9	1·9	6	3·8	3·8	10	6·4	6·4
S3	17	7·3	8·2	53	25·4	27·3	44	28·0	31·8	49	31·6	38·0
S2+	25	10·7	18·9	31	14·8	42·1	28	17·8	49·6	24	15·5	53·5
S2	189	81·1	100·0	121	57·9	100·0	79	50·4	100·0	72	44·5	100·0
Total	233			209			157			155		

* Delay less than 6 months. Resection less than 5 cm.

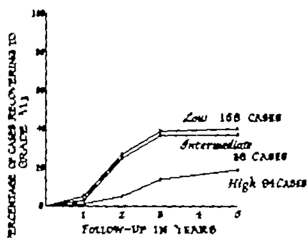


FIG 257 Median nerve motor recovery in relation to site of suture.

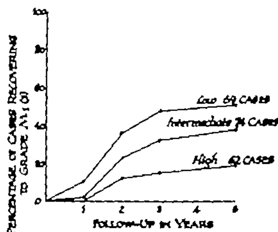


FIG 258. Lateral popliteal nerve motor recovery in relation to site of suture.

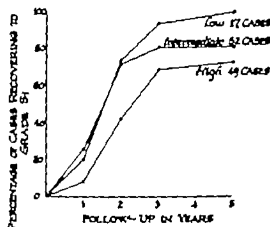


FIG. 259 Medial popliteal ...

delay can be studied Only sutures performed at approximately the same level must be considered for example all low or all high sutures Similarly the effect of the length of resection must be excluded by restricting the analysis to cases in which the gap after resection was less than 5 cm.

Tables 91–98 give the results in relation to delay before suture in two groups according to whether suture was performed sooner or later than six months after injury The figures clearly favour early suture, but the difference between the numbers of early and later sutures making a useful recovery was significant only for sensory recovery after low median or low ulnar nerve repair Sixty-eight per cent of these early median sutures made a useful sensory recovery compared with 33 per cent of late sutures (Fig. 260). The figures for motor recovery to a useful grade

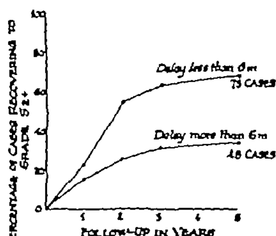


FIG. 260 Median nerve sensory recovery in relation to delay before suture. (Low sutures only resection less than 5 cm.)

TABLE 84

*Ulnar nerve sensory recovery in relation to site of suture**

Grade of recovery	Follow-up in years: 1			2			3			5		
	No.	%	C%	No.	%	C%	No.	%	C%	No.	%	C%
High S3+												
S3	4	3·1	3·1	18	14·7	14·7	21	20·0	20·0	23	22·9	22·9
S2+	5	3·8	6·9	15	12·3	27·0	26	24·8	44·8	4	23·8	46·7
S2	121	93·1	100·0	89	73·0	100·0	58	55·2	100·0	56	53·3	100·0
Total	130			122			105			105		
Intermediate S3+												
S3	7	4·6	4·6	23	15·2	15	33	25·4	25·4	36	27·7	27·7
S2+	13	8·6	13·2	22	14·6	29·8	12	9·2	34·6	11	8·5	36·
S2	132	86·8	100·0	106	70·	100·0	85	65·4	100·0	83	63·8	100·0
Total	152			151			130			130		
Low S3+	2	0·9	0·9	4	1·9	1·9	6	3·8	3·8	10	6·4	6·4
S3	17	7·3	8·2	53	25·4	27·3	44	28·0	31·8	49	31·6	38·0
S2+	25	10·7	18·9	31	14·8	42·1	28	17·8	49·6	24	15·5	53·5
S2	189	81·1	100·0	121	57·9	100·0	79	50·4	100·0	72	46·5	100·0
Total	233			209			157			155		

* Delay less than 6 months. Resection less than 5 cm.

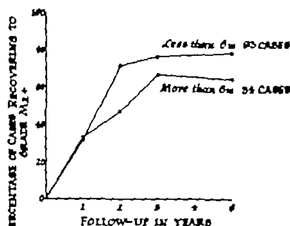


FIG. 261 Ulnar nerve motor recovery in relation to delay before suture. (Low sutures only resection less than 5 cm.)

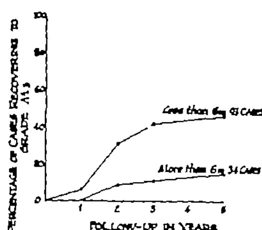


FIG. 262. Ulnar nerve motor recovery in relation to delay before suture. (Low sutures only resection less than 5 cm.)

after repair of the ulnar nerve show a difference, but not a significant one as between early and late sutures (Fig. 261) However there was a considerable and significant difference (Fig. 262) in the number reaching a higher grade of recovery so that long delay certainly was an obstacle to *good* recovery although it might not have influenced the number making a *useful* recovery

TABLE 85

*Median nerve motor recovery in relation to site of suture**

Grade of recovery	Follow-up in years: 1			2			3			5		
	No.	%	C%	No.	%	C%	No.	%	C%	No.	%	C%
High M4				1	1·0	1·0	6	6·4	6·4	6	6·4	6·4
M3	2	1·9	1·9	4	4·0	5·0	8	8·5	14·9	12	12·8	19·2
M2	4	3·8	5·7	41	41·0	46·0	43	45·7	60·6	39	41·5	60·7
M1+	27	25·7	31·4	32	32·0	78·0	25	26·6	87·2	26	27·6	88·3
M1	72	68·6	100·0	22	22·0	100·0	12	12·8	100·0	11	11·7	100·0
Total	105			100			94			94		
Intermediate M4	2	3·5	3·5	5	10·9	10·9	7	18·4	18·4	7	18·4	18·4
M3	—	—	3·5	7	15·2	26·1	7	18·4	36·8	7	18·4	36·8
M2	11	19·3	22·8	12	26·1	52·2	9	23·7	60·5	9	23·7	60·5
M1+	44	77·2	100·0	22	47·8	100·0	15	39·5	100·0	15	39·5	100·0
Total	57			46			38			38		
Low M4	5	2·8	2·8	25	14·4	14·4	36	23·1	23·1	41	26·0	26·0
M3	4	2·2	5·0	22	12·6	27·0	24	15·4	38·5	22	13·8	39·8
M2	54	30·3	35·3	56	32·2	59·2	40	25·6	64·1	41	26·9	65·8
M1+	116	64·7	100·0	71	40·8	100·0	56	35·9	100·0	54	34·2	100·0
Total	179			174			156			158		

* Delay less than 6 months Resection less than 5 cm.

Is there any limit of delay beyond which useful recovery is unlikely to follow suture? The critical delay for cases in all five Nerve Injuries Centres is shown in Table 99. Useful motor recovery did not occur after a delay of more than eighteen months except after low median sutures in which a useful range of abduction of the thumb was regained when the delay before operation was two and a half years. The critical delay for sensory recovery was considerably longer—from two to three years.

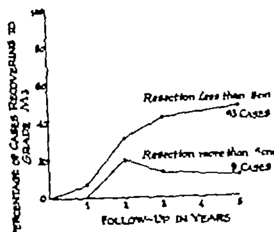


FIG. 263. Ulnar nerve: motor recovery in relation to length of resection. (Low sutures only: delay less than 6 months.)

No separate grouping of primary nerve sutures has been made in this analysis: they have been included in the group of early sutures and it is unlikely that this arrangement has prejudiced the results. Many primary sutures were explored at the Centres soon after repair and if the appearance of the suture was unsatisfactory the lesion was resected and the nerve resutured. Thus the record of recoveries after primary sutures would be a selected group with many of

TABLE 86

*Median nerve: sensory recovery in relation to site of suture**

Grade of recovery	Follow-up in years: 1 No.	1 %	1 C%	2 No.	2 %	2 C%	3 No.	3 %	3 C%	5 No.	5 %	5 C%
High S3+							4	4·2	4·2	5	5·4	5·4
S3	2	1·8	1·8	16	15·5	15·5	23	24·2	28·4	23	24·7	30·1
S2+	3	2·7	4·5	16	15·5	31·0	23	24·2	52·6	21	22·6	52·7
S2	105	95·5	100·0	73	69·0	100·0	45	47·4	100·0	44	47·3	100·0
Total	110			105			95			93		
Intermediate S3+				1	2·2	2·2	3	7·5	7·5	3	7·5	7·5
S3	1	2·1	2·1	9	19·5	21·7	13	32·5	40·0	13	32·5	40·0
S2+	6	12·5	14·6	6	13·0	34·7	3	7·5	47·5	3	7·5	47·5
S2	41	85·4	100·0	30	65·3	100·0	21	52·5	100·0	21	52·5	100·0
Total	48			46			40			40		
Low S3+	1	0·5	0·5	3	1·7	1·7	11	7·6	7·6	16	11·0	11·0
S3	17	8·9	9·4	37	21·5	[illegible]	46	32·0	39·6	46	31·7	42·7
S2+	25	13·0	[illegible]	36	20·9	44·1	18	1·5	52·1	18	12·4	55·1
S2	149	77·6	100·0	96	55·9	100·0	69	47·9	100·0	65	44·9	100·0
Total	192			172			144			145		

* Delay less than 6 months. Resection less than 5 cm.

the poor results missing because the nerves had been resutured. Moreover it has been shown (Zachary and Holmes, 1946) that there is no intrinsic merit in repair at the primary operation when compared with early secondary suture. Primary and early secondary sutures have therefore been considered as one group.

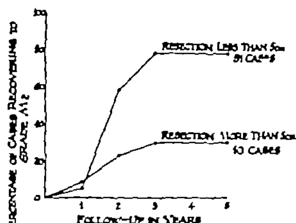


Fig 264 Median nerve motor recovery in relation to length of resection. (High sutures only delay less than 6 months.)

(iii) *Length of Resection*

Tables 100–107 give the results in relation to length of resection in two groups, those in which the resection was less than 5 cm. and those in which it was 5 cm or more. The other two factors were eliminated by considering one particular site of suture (low intermediate, or high) and discarding all cases with a delay before suture of more than six months.

TABLE 87

*Radial nerve motor recovery in relation to site of suture**

Grade of recovery	Follow-up in years											
	1			2			3			5		
	No.	%	C%	No.	%	C%	No.	%	C%	No.	%	C%
High M4	2	5·4	5·4	7	24·1	24·1	6	26·1	26·1	6	26·1	26·1
M3	1	2·7	8·1	5	17·3	41·4	4	17·4	43·5	4	17·4	43·5
M2	13	35·2	43·3	10	34·5	75·9	9	39·1	83·2	9	39·1	83·2
M1	21	56·7	100·0	7	24·1	100·0	4	17·4	100·0	4	17·4	100·0
Total	37			29			23			23		
Intermediate M4	4	3·0	3·0	19	17·9	17·9	34	42·5	42·5	35	43·0	43·2
M3	21	15·5	18·5	33	31·1	49·0	18	22·5	65·0	18	22·3	65·5
M2	67	49·6	68·1	40	37·9	86·9	20	25·0	90·0	21	26·0	91·5
M1	43	31·9	100·0	14	13·1	100·0	8	10·0	100·0	7	8·5	100·0
Total	135			106			80			81		
Low M4	3	13·0	13·0	5	22·8	22·8	1	10·0	10·0	1	10·0	10·0
M3	9	39	52·2	7	31·8	54·6	6	60·0	70·0	6	60·0	70·0
M2	6	26·1	78·3	7	31·8	86·4	2	20·0	90·0	2	20·0	90·0
M1	5	21·7	100·0	3	13·6	100·0	1	10·0	100·0	1	10·0	100·0
Total	23			22			10			10		

* Delay less than 6 months. Resection less than 5 cm.

The differences are not so striking as those for level of suture, but in two instances a significant difference could be found—in the higher grades of motor recovery for the ulnar (Fig. 263) and median nerves (Fig. 264)

At first sight it may seem strange that so little difference should be found in two groups of long and short resections Theoretically the adverse effects of long resection are the great incongruity of the funicular pattern in the two segments of the nerve, and the increased tension at the suture line Yet within limits the importance of the latter factor can be reduced by good operative technique and adequate mobilization of the nerve indeed, there may be greater tension after inadequate mobilization for a moderate resection than after adequate freeing of the stumps for long resection. The most striking example was in repair of the ulnar nerve in the forearm with and without transposition at the elbow It is possible, and indeed likely that the figures do not represent the full effects of the length of resection. Some other means of assessing its importance is required

Where the gap was very great the mobilization was maximal and it was among such cases that a true estimate of the influence of the length of resection was found. From the combined results the greatest lengths of resection compatible with recovery have been determined the particular grade of recovery is indicated for each case under review (Table 108)

TABLE 88

*Medial popliteal nerve motor recovery in relation to site of suture**

Grade of recovery	Follow-up in years											
	1			2			3			5		
	No.	%	C%	No	%	C%	No.	%	C%	No.	%	C%
High M1 (4+)	2	3·5	3·5	7	11·7	11·7	9	17·3	17·3	10	18·5	18·5
M1 (4)	5	8·8	12·3	14	23·3	35·0	14	26·8	44·1	18	33·3	51·8
M1 (3)	9	15·8	28·1	14	23·3	58·3	12	23·2	67·3	10	18·5	70·3
M1 (2)	41	71·9	100·0	25	41·7	100·0	17	32·7	100·0	16	29·7	100·0
Total	57			60			52			54		
Intermediate M1 (4+)	1	1·7	1·7	13	20·0	20·0	16	29·7	29·7	17	30·4	30·4
M1 (4)	9	15·0	16·7	19	29·2	49·2	14	25·9	55·6	20	35·7	64·1
M1 (3)	15	25·0	41·7	9	13·9	63·1	9	16·6	72·2	8	14·3	80·4
M1 (2)	35	58·3	100·0	24	36·9	100·0	15	27·8	100·0	11	19·6	100·0
Total	60			65			54			56		
Low M1 (4+)	1	6·2	6·2	5	23·8	23·8	5	31·3	31·3	5	31·3	31·3
M1 (4)				2	9·5	33·3	1	6·1	37·4	1	6·1	37·4
M1 (3)	5	31·3	37·5	6	28·6	61·9	5	31·3	68·7	5	31·3	68·7
M1 (2)	10	62·5	100·0	8	38·1	100·0	5	31·3	100·0	5	31·3	100·0
Total	16			21			16			16		

* Delay less than 6 months. Resection less than 5 cm.

The longest resection to be followed by useful recovery was 13 cm. of the ulnar nerve at the elbow For the other nerves the figures ranged from 8 to 11 cm.

It must be remembered that these recoveries were exceptional results in a large series of cases, and it cannot be assumed that a resection of say 9 cm. of the median nerve is *likely* to be followed by good sensory recovery However if there is no satisfactory alternative, the possibility of such a result justifies the operation of nerve suture. It is at this point that the possibility of using alternative methods of repair such as grafting must be considered The results of grafting should not be compared with ordinary suture results but with recoveries after long resection If for the exceptional result obtained by suture after resection of 9 cm. can be substituted an even chance, or better obtained by grafting, the latter procedure is to be preferred.

TABLE 89

*Medial popliteal sensory recovery in relation to site of suture**

Grade of recovery	Follow-up in years											
	1			2			3			5		
	No.	%	C%	No.	%	C%	No.	%	C%	No.	%	C%
High S3							1	2·0	2·0	1	2·0	0
S2+												
S2				3	5·1	5·1	5	10·2	12·2	6	12·4	14·4
S1	5	7·5	7·5	23	37·3	42·4	28	57·2	69·4	29	59·2	73·6
S0	62	92·5	100·0	33	57·6	100·0	15	30·6	100·0	13	26·4	100·0
Total	67			59			49			49		
Intermediate S3				3	4·9	4·9	2	3·8	3·8	5	9·6	9·6
S2−				2	3·3	8·2	2	3·8	7·6	2	3·8	13·4
S2	2	3·0	3·0	9	14·7	22·9	13	25·0	32·6	13	25·0	38·4
S1	15	22·8	25·8	30	49	72·1	25	48·1	80·7	22	42·3	80·7
S0	49	74·2	100·0	17	27·9	100·0	10	19·3	100·0	10	19·3	100·0
Total	66			61			52			32		
Low S3							2	11·8	11·8	2	11·8	11·8
S2−				4	14·8	14·8						
S2	1	4·2	4·2	6	22·2	37·0	3	17·6	29·4	3	17·6	29·4
S1	4	16·6	20·8	10	37·0	74·0	11	64·7	94·1	12	70·6	100·0
S0	19	79·2	100·0	7	26·0	100·0	1	5·9	100·0			
Total	24			27			17			[illegible]		

* Delay less than 6 months. Resection less than 7 cm.

TABLE 90

*Lateral popliteal nerve motor recovery in relation to site of suture**

Grade of recovery	Follow-up in years: 1			2			3			4		
	No.		C %	No	%	C	No.	%	C %	No.	%	C
High M1 (4)				1	1·4	1·4				4	6·5	6·5
M1 (3)				8	11·0	12·4	9	15·0	15·0	8	12·9	19·4
M1 (2)	3	4·2	4·2	7	9·6	2[illegible]·0	10	16·7	31·7	8	12·9	32·3
M1 (1)	69	95·8	100·0	57	78·0	100·0	41	68·3	100·0	42	67·7	100·0
Total	72			73			60			62		
Intermediate M1 (4)				5	5·5	5·5	8	10·8	10·8	10	13·5	13·5
M1 (3)	2	2·1	2·1	16	17·6	23·1	16	21·6	32·4	17	23·0	36·5
M1 (2)	10	10·3	12·4	14	15·4	38·5	13	17·6	50·0	12	16·2	54·7
M1 (1)	85	87·6	100·0	56	61·5	100·0	37	50·0	100·0	35	47·3	100·0
Total	97			91			74			74		
Low M1 (4)		2·1	2·1	14	16·3	16·3	12	17·4	17·4	14	20·2	20·2
M1 (3)	8	8·4	10·5	17	19·8	36·1	21	30·5	47·9	21	30·5	50·7
M1 (2)	17	17·9	28·4	22	25·6	61·7	14	20·3	68·2	13	18·8	69·5
M1 (1)	68	71·6	100·0	33	38·3	100·0	22	31·8	100·0	21	30·5	100·0
Total	95			86			69			69		

* Delay less than 6 months. Resection less than 5 cm.

4 Conclusions

In general repair of a divided nerve gives an even chance of useful recovery that is, the return of sufficient function to make the suture worth while. The prospects vary somewhat from nerve to nerve, and are altered by factors such as the level of suture, delay before suture and the gap after resection of the damaged portion The results might be considerably better in a series of cases resulting from peace time accidents. Perfect recovery is rare, possibly it never occurs but there has been a close approach to perfection in a few radial nerve sutures, and in occasional sutures of the median nerve in children In almost one third of the radial nerve sutures, even under good conditions, there is still defective independent movement of the fingers and after median nerve suture two-point discrimination is regained in approximately only 10 per cent of cases

Ulnar nerve sutures have a bad reputation probably because the simple and well known test of lateral movement of the fingers is one which is passed only by patients with the highest grade of recovery Yet useful return of power to the intrinsic muscles occurs after 71 per cent of low sutures.

Recovery after repair of the sciatic nerve has often been considered so poor that where the nerve has been divided amputation of the leg has been seriously

advocated Yet strong action returns to the calf muscle in at least half the cases, even including those in which the lesion is in the buttock. Sensory recovery is admittedly poor but 80 per cent of patients can feel a strong painful stimulus in the foot. Moreover, even among those with complete sensory loss in the foot there are many patients with good function of the limb

Recovery after suture of the lateral popliteal nerve is poor but some late improvement has brought a number of patients into the category of those with useful recovery Only one in five high sutures prove to be worth while, whereas half the low sutures are followed by an adequate recovery Although one patient in eight regains dorsiflexion of the foot against resistance, a number of these are not able to dispense altogether with a toe raising spring.

Many patients who show early signs of recovery continue to make good progress there are others whose early recovery is slow and if judged at the end of two years they would be considered failures. Yet three years after suture they reach a useful recovery and some patients continue to improve up to five years after repair It is clear that no assessment of recovery should be regarded as final before three years have elapsed.

A high level of suture, delay and extensive resection have been shown to affect the outlook unfavourably The level and extent of damage to the nerve are always beyond control and the duration of the delay sometimes so The existence of other significant factors is indicated.

The number of poor recoveries after treatment under good conditions is large enough to be important. This should preclude an attitude of complacency with present methods of treatment of peripheral nerve injuries and stimulate a search for better ones both operative and conservative.

Tables 91–108

TABLE 91

*Ulnar nerve motor recovery in relation to delay before suture**

Grade of recovery	Follow-up in years											
	1			2			3			5		
	No.	%	C%	No.	%	C%	No.	%	C%	No.	%	C%
Delay less than 6 months M4	2	1·4	1·4	11	8·6	8·6	15	16·1	16·1	15	16·1	16·1
M3	7	5·0	6·4	29	22·7	31·3	24	25·8	41·9	29	31·2	47·3
M2+	36	25·5	31·9	52	40·6	71·9	33	35·5	77·4	29	31·2	78·5
M2	96	68·1	100·0	36	28·1	100·0	21	22·6	100·0	20	21·5	100·0
Total	141			128			93			93		
Delay more than 6 months M4				1	2·2	2·2	2	5·9	5·9	2	5·9	5·9
M3				3	6·7	8·9	2	5·9	11·8	3	8·8	14·7
M2	16	33·3	33·3	17	37·8	46·7	19	55·8	67·6	17	50·0	64·7
M2	32	66·7	100·0	24	53·3	100·0	11	32·4	100·0	12	35·3	100·0
Total	48			45			34			34		

* Low sutures only Resection less than 5 cm.

TABLE 94

*Median nerve sensory recovery in relation to delay before suture**

Grade of recovery	Follow-up in years: 1			2			3			5		
	No.	%	C%	No.	%	C%	No.	%	C%	No.	%	C%
Delay less than 6 months S3				1	1.3	1.3	8	10.8	10.8	10	13.3	13.3
S3	11	10.7	10.7	23	28.3	29.6	28	38.0	48.8	29	38.7	52.0
S2+	12	11.6	22.3	22	25.0	54.6	11	14.7	63.5	12	16.0	68.0
S2	80	77.7	100.0	40	45.4	100.0	27	36.5	100.0	24	12.0	100.0
Total	103			88			74			75		
Delay more than 6 months S3+	1	1.7	1.7	2	3.5	3.5	3	6.2	6.2	5	10.4	10.4
S3	3	5.3	7.0	5	8.8	12.3	9	18.7	24.9	8	16.7	27.1
S2+	5	8.6	15.6	7	12.3	24.6	3	6.2	31.1	3	6.2	33.3
S2	49	84.4	100.0	43	75.4	100.0	33	68.9	100.0	32	66.7	100.0
Total	58			57			48			48		

* Low sutures only. Resection less than 5 cm.

TABLE 95

*Radial nerve motor recovery in relation to delay before suture**

Grade of recovery	Follow-up in years: 1			2			3			5		
	No.	%	C%	No.	%	C%	No.	%	C%	No.	%	C%
Delay less than 6 months M4	3	3.8	3.8	13	22.0	22.0	22	50.0	50.0	23	51.1	51.1
M3	15	19.5	23.3	21	35.5	57.5	9	20.4	70.4	9	20.0	71.1
M2	42	53.6	76.9	19	32.3	89.8	9	20.4	90.8	9	20.0	91.1
M1	18	23.1	100.0	6	10.2	100.0	4	9.2	100.0	4	8.9	100.0
Total	78						44			45		
Delay more than 6 months M4				3	13.0	13.0	6	31.6	31.6	6	31.6	31.6
M3	2	6.2	6.2	5	21.7	34.7	4	21.1	52.7	4	21.1	52.7
M2	15	46.9	53.1	12	52.3	87.0	7	36.7	89.4	7	36.7	89.4
M1	15	46.9	100.0	3	13.0	100.0	2	10.6	100.0	2	10.6	100.0
Total	32			23			19			19		

* Intermediate sutures only. Resection less than 5 cm.

LE 99

th recovery to specific grade

	Grade of recovery	Delay (months)
	M2	9
	M2 +	16
	M2 +	18
	S3	9
	S3	24
	S3	31
	M1 +	9
	M3	13
	M3	32
	S3	12
	S3	36 child 17 adult
	S3	26 child 9 adult
	M3	13
	M3	16
	M3	9
	M1 (3)	12
	M1 (3)	13
	M1 (3)	12
tor)	M1 (4)	13
	M1 (4)	15
	M1 (4)	12

TABLE 98

*Lateral popliteal nerve motor recovery in relation to delay before suture**

Grade of recovery	Follow-up in years											
	1			2			3			5		
	No.	%	C%	No.	%	C%	No.	%	C%	No.	%	C%
Delay less than 6 months												
M1 (4)	2	6·9	6·9	8	32·0	32·0	6	27·3	27·3	7	31·8	31·8
M1 (3)	6	20·7	27·6	8	32·0	64·0	7	31·8	59·1	6	27·3	59·1
M1 (2)	8	27·6	55·2	2	8·0	72·0	2	9·1	68·2	2	9·1	68·2
M1 (1)	13	44·8	100·0	7	28·0	100·0	7	31·8	100·0	7	31·8	100·0
Total	29			25			22			22		
Delay more than 6 months												
M1 (4)				2	7·4	7·4	3	13·6	13·6	3	13·6	13·6
M1 (3)	1	3·8	3·8	4	14·8	22·2	6	27·3	40·9	7	31·8	45·4
M1 (2)	2	7·7	11·5	9	33·3	55·5	6	27·3	68·2	5	22·8	68·2
M1 (1)	23	88·5	100·0	12	44·5	100·0	7	31·8	100·0	7	31·8	100·0
Total	26			27			22			22		

Low sutures only Retraction less than 5 cm.

TABLE 99

Critical delay compatible with recovery to specific grade

Nerve and site	Grade of recovery	Delay (months)
Ulnar (motor)		
High	M2	9
Intermediate	M2 +	16
Low	M2 +	18
Ulnar (sensory)		
High	S3	9
Intermediate	S3	24
Low	S3	31
Median (motor)		
High	M1 +	9
Intermediate	M3	13
Low	M3	32
Median (sensory)		
High	S3	12
Intermediate	S3	36 child 17 adult
Low	S3	26 child 9 adult
Radial		
High	M3	13
Intermediate	M3	16
Low	M3	9
Lateral popliteal		
High	M1 (3)	12
Intermediate	M1 (3)	13
Low	M1 (3)	12
Medial popliteal (motor)		
High	M1 (4)	13
Intermediate	M1 (4)	15
Low	M1 (4)	12
Medial (sensory)		
High	S2	15
Intermediate	S2	14
Low	S2	12

TABLE 100

*Ulnar nerve motor recovery in relation to length of resection**

Grade of recovery	Follow-up in years: 1			2			3			4		
	No.	%	C%	No.	%	C%	No.	%	C%	No.	%	C%
Resection less than 5 cm. M4	2	1·4	1·4	11	8·6	8·6	15	16·1	16·1	15	16·1	16·1
M3	7	5·0	6·4	29	22·7	31·1	24	25·8	41·9	29	31·2	47·3
M2+	36	25·5	31·9	52	40·6	71·9	33	35·5	77·4	29	31·2	78·5
M2	96	68·1	100·0	36	28·1	100·0	21	22·6	100·0	20	21·5	100·0
Total	141			128			93			93		
Resection more than 5 cm. M4												
M3				3	20·0	20·0	1	12·5	12·5	1	11·1	11·1
M2+	2	14·3	14·3	3	20·0	40·0	4	50·0	62·5	5	55·6	66·7
M2	12	85·7	100·0	9	60·0	100·0	3	37·5	100·0	3	33·3	100·0
Total	14			15			8			9		

* Low sutures only. Delay less than 6 months.

TABLE 101

*Ulnar nerve sensory recovery in relation to length of resection**

Grade of recovery	Follow-up in years: 1			2			3			5		
	No.	%	C%	No.	%	C%	No.	%	C%	No.	%	C%
Resection less than 5 cm. S3+	2	1·4	1·4	3	2·4	2·4	5	5·3	5·3	9	9·7	9·7
S3	14	9·8	11·2	40	31·7	34·1	34	35·7	41·6	37	39·8	49·5
S2+	22	15·3	26·5	18	14·3	48·4	17	17·8	58·8	14	15·1	64·6
S2	105	73·5	100·0	65	51·6	100·0	39	41·2	100·0	33	35·4	100·0
Total	143			126			95			93		
Resection more than 5 cm. S3+												
S3				4	25·0	25·0	5	50·0	50·0	5	55·6	55·6
S2	1	6·2	6·2	4	25·0	50·0	1	10·0	60·0	1	11·1	66·7
S2	15	93·8	100·0	8	50·0	100·0	4	40·0	100·0	3	33·3	100·0
Total	16			16			10			9		

* Low sutures only. Delay less than 6 months.

TABLE 102

*Median nerve motor recovery in relation to length of resection**

Grade of recovery	Follow-up in years: 1			2			3			5		
	No.	%	C%	No.	%	C%	No.	%	C%	No.	%	C%
Resection less than 5 cm. 4				1	1·9	1·9	5	9·8	9·8	5	9·8	9·8
3	1	1·8	1·8	3	5·7	7·6	6	11·7	21·5	8	15·7	25·5
	2	3·6	5·4	27	50·8	58·4	29	56·9	78·4	27	52·9	78·4
1+	19	33·9	39·3	15	28·2	86·0	8	15·7	94·1	8	15·7	94·1
1	34	60·7	100·0	7	13·4	100·0	3	5·9	100·0	3	5·9	100·0
Total	56			53			51			51		
Resection more than 5 cm. 4												
3	1	8·3	8·3							1	10·0	10·0
2			8·3	2	22·2	22·2	3	30·0	30·0	2	20·0	30·0
1+	5	41·7	50·0	5	55·6	77·8	6	60·0	90·0	6	60·0	90·0
1	6	50·0	100·0	2	22·2	100·0	1	10·0	100·0	1	10·0	100·0
Total	12			9			10			10		

* High sutures only. Delay less than 6 months.

TABLE 103

*Median nerve sensory recovery in relation to length of resection**

Grade of recovery	Follow-up in years: 1						3			5		
	No.	%	C%	No.	%	C%	No.	%	C%	No.	%	C%
Resection less than 5 cm. S3+				1	1·3	1·3	8	10·8	10·8	10	13·3	13·3
S3	11	10·7	10·7	25	28·3	29·6	28	38·6	48·8	29	38·7	52·0
S2	12	11·6	22·3	22	25·0	54·6	11	14·7	63·5	12	16·0	68·0
S2	80	77·7	100·0	40	45·4	100·0	27	36·5	100·0	34	32·0	100·0
Total	103			88			74			75		
Resection more than 5 cm. S3+												
S3				3	33·3	33·3	3	50·0	50·0	3	50·0	50·0
S[illegible]	5	55·6	55·6	3	33·4	66·7	1	16·7	66·7	1	16·7	66·7
S[illegible]	4	44·4	100·0	3	33·3	100·0	2	33·3	100·0	2	33·3	100·0
Total	9			9			6			6		

* Low sutures only. Delay less than 6 months.

TABLE 104

*Radial nerve motor recovery in relation to length of resection**

Grade of recovery	Follow-up in years											
	1			2			3			5		
	No.	%	C%	No.	%	C%	No.	%	C%	No.	%	C%
Resection less than 5 cm. M4	3	3·8	3·8	13	22·0	22·0	22	54·0	50·0	23	51·1	51·1
M3	15	19·5	23·3	21	35·5	57·5	9	20·4	70·4	9	20·0	71·1
M2	42	53·6	76·9	19	32·3	89·8	9	20·4	90·8	9	20·1	91·1
M1	18	23·1	100·0	6	10·2	100·0	4	9·2	100·0	4	8·9	100·0
Total	78			59			44			45		
Resection more than 5 cm. M4	1	10·0	10·0	3	30·0	30·0	4	50·0	50·0	4	50·0	50·0
M3	3	30·0	40·0	3	30·0	60·0	3	37·5	87·5	3	37·5	87·5
M2	6	60·0	100·0	4	40·0	100·0	1	12·5	100·0	1	12·5	100·0
M1												
Total	10			10			8			8		

* Intermediate sutures only. Delay less than 6 months

TABLE 105

*Medial popliteal nerve motor recovery in relation to length of resection**

Grade of recovery	Follow-up in years											
	1			2			3			5		
	No.	%	C%	No.	%	C%	No.	%	C%	No.	%	C%
Resection less than 5 cm. M1 (4+)	1	4·5	4·5	4	18·2	18·2	7	33·3	33·3	7	31·8	31·8
M1 (4)	6	27·3	31·8	7	31·8	50·0	5	23·9	57·2	9	41·0	72·8
M1 (3)	5	22·7	54·5	2	9·1	59·1	2	9·5	66·7	1	4·5	77·3
M1 (2)	10	45·5	100·0	9	40·9	100·0	7	33·3	100·0	5	22·7	100·0
Total	22			22			21			22		
Resection more than 5 cm M1 (4+)				5	25·0	25·0	4	28·6	28·6	4	28·6	28·6
M1 (4)	2	11·8	11·8	6	30·0	55·0	2	14·3	42·9	2	14·3	42·9
M1 (3)	5	29·4	41·2	3	15·0	70·0	5	35·7	78·6	5	35·7	78·6
M1 (2)	10	58·8	100·0	6	30·0	100·0	3	21·4	100·0	3	21·4	100·0
Total	17			20			14			14		

* Intermediate sutures only. Delay less than 6 months

TABLE 106

*Medial popliteal nerve sensory recovery in relation to length of resection**

Grade of recovery	Follow-up in years: 1			2			3			5		
	No.	%	C	No.	%	C%	No.	%	C	No.	%	C
Resection less than 5 cm. S3										2	10·0	10·0
S2+												
S2				4	19·0	19·0	7	35·0	35·0	7	35·0	45·0
S1+	24	100·0	100·0	17	81·0	100·0	13	65·0	100·0	11	55·0	100·0
Total	24			21			20			20		
Resection more than 5 cm. S3				3	15·8	15·8	2	15·4	15·4	3	23·6	23·0
S2+				2	10·5	26·3	2	15·4	30·8	2	15·4	48·4
S2	2	10·0	10·0	3	15·8	42·1	4	30·8	61·6	4	30·8	69·2
S1+	18	90·0	100·0	11	57·9	100·0	5	38·4	100·0	4	30·8	100·0
Total	20			19			13			13		

* Intermediate sutures only Delay less than 6 months

TABLE 107

*Lateral popliteal nerve motor recovery in relation to length of resection**

Grade of recovery	Follow-up in years: 1			2			3			4		
	No.		C%	No.	%	C%	No	%	C%	No.	%	C%
Resection less than 5 cm. M1 (4)	2	6·9	6·9	8	32·0	32·0	6	27·3	27·3	7	31·8	31·8
M1 (3)	6	20·7	27·6	8	32·0	64·0	7	31·8	59·1	6	27·3	59·1
M1 (2)	8	27·6	55·2	2	8·0	72·0	2	9·1	68·2	2	9·1	68
M1 (1)	13	44·8	100·0	7	28·0	100·0	7	31·8	100·0	7	31·8	100·0
Total	29			25			22			22		
Resection more than 5 cm. M1 (4)				2	11·8	11·8	2	20·0	20·0	2	20·0	20·0
M1 (3)	1	4·0	4·0	3	17·6	29·4	3	30·0	50·0	3	30·0	30·0
M1 (2)	7	28·0	32·0	5	29·4	58·8	2	20·0	70·0	2	20·0	50·0
M1 (1)	17	68·0	100·0	7	41·2	100·0	3	30·0	100·0	3	30·0	100·0
Total	25			17			10			10		

* Low sutures only Delay less than 6 months

TABLE 108

Critical resection in cm compatible with recovery to specific grade

Nerve and site	Grade of recovery	Length of resection (cm.)
Ulnar (motor)		
High	M2 +	10
Intermediate	M2 +	13
Low	M2 +	10
Ulnar (sensory)		
High	S3	9 2
Intermediate	S3	13
Low	S3	10
Median (motor)		
High	M1 +	7
Intermediate	M3	8 5
Low	M3	7
Median (sensory)		
High	S3	7
Intermediate	S3	9
Low	S3	7 5
Radial		
High	M3	8
Intermediate	M3	8
Low	M3	7 5
Lateral popliteal		
High	M1 (3)	9
Intermediate	M1 (3)	8 8
Low	M1 (3)	9
Medial popliteal (motor)		
High	M1 (4)	11 5
Intermediate	M1 (4)	11
Low	M1 (4)	8
Medial (sensory)		
High	S2	10
Intermediate	S2	11
Low	S2	7

IX

NERVE GRAFTING AND OTHER UNUSUAL FORMS OF NERVE REPAIR

by H J SEDDON

1 Nerve Grafting

A INTRODUCTION

DURING the First World War end to-end suture became established as the only reliable form of nerve repair The technique of the operation was perfected, and by means of extensive mobilization of the nerve stumps it became possible to close very large gaps. Nerve grafting, on the other hand, remained under a cloud very few functionally satisfactory results were reported The problem of closure of the large gap had not been completely solved Furthermore, it was not until the Second World War that it was appreciated that the closure of large gaps by suture was not devoid of risk. It was then found that in cases where the gap was of the order of 10 cm. the post-operative stretching, how ever carefully carried out, generally damaged the nerve to such an extent as to preclude recovery (Highet and Holmes, 1943 Highet and Sanders, 1943)

In an analysis of 699 cases requiring operative repair Seddon (1947b) found that suture was possible in 499 (71 per cent) that an extraordinary form of repair was required in 65 (9 4 per cent) and that in 135 (19 5 per cent) nothing could be done because the extent of the lesion was too great. The cases treated by suture included a number in which the gap was considerable and in which no recovery had occurred. He pointed out that the proportion in which suture was desirable—not merely technically possible—was therefore, appreciably less than 70 per cent

Bulb suture and bone shortening are familiar devices for facilitating end to-end suture in the marginal case Hoen s selective stretching of the central stump (see Seddon 1949a) is a variant of bulb suture although final results in his cases are not yet available, it promises to be a valuable technical advance But the crux of the problem is whether nerve grafting is, after all a useful method of repair Between the wars there were a few encouraging advances. Bunnell (1927) established grafting as a reliable method for repairing digital nerves followed by Ballance and Duel (1932) and Duel (1933), he was also successful in grafting the facial nerve (1937) In 1939 Bunnell and Boyes, and in 1943 Klar reported cases of injury to the main nerve trunks in the limbs in which useful recovery followed repair by grafting. In all but one of Ballance s cases the grafts were autogenous

The ideal material would be a graft from another species or from another person, and preferably one that could be stored. Unfortunately all exogenous grafts have proved unsatisfactory Heterogenous nerve grafting is useless Fresh and stored homografts although promising experimentally have been tried at two of the British centres (Seddon and Holmes 1944 Barnes, Bacsich Wyburn and Kerr 1946) and by Spurling, Lyons, Whitcomb and Woodhall (1945) in the American Army and have been found wanting. Seddon and Holmes (1944) suggested that their failure was analogous to that of homogenous skin grafts which as Gibson and Medawar (1943) showed was due to the development of an active immunity to the transplanted tissue

TABLE 108

Critical resection in cm. compatible with recovery to specific grade

Nerve and site	Grade of recovery	Length of resection (cm.)
Ulnar (motor)		
High	M2 +	10
Intermediate	M2 +	13
Low	M2 +	10
Ulnar (sensory)		
High	S3	9 2
Intermediate	S3	13
Low	S3	10
Median (motor)		
High	M1 −	7
Intermediate	M3	8 5
Low	M3	-
Median (sensory)		
High	S3	-
Intermediate	S3	9
Low	S3	7 5
Radial		
High	M3	8
Intermediate	M3	8
Low	M3	- 5
Lateral popliteal		
High	M1 (3)	9
Intermediate	M1 (3)	8 8
Low	M1 (3)	9
Medial popliteal (motor)		
High	M1 (4)	11 5
Intermediate	M1 (4)	11
Low	M1 (4)	8
Medial (sensory)		
High	S2	10
Intermediate	S2	11
Low	S2	7

IX

NERVE GRAFTING AND OTHER UNUSUAL FORMS OF NERVE REPAIR

by H J SEDDON

1 Nerve Grafting

A INTRODUCTION

DURING the First World War end to-end suture became established as the only reliable form of nerve repair The technique of the operation was perfected and by means of extensive mobilization of the nerve stumps it became possible to close very large gaps. Nerve grafting, on the other hand remained under a cloud very few functionally satisfactory results were reported The problem of closure of the large gap had not been completely solved Furthermore it was not until the Second World War that it was appreciated that the closure of large gaps by suture was not devoid of risk. It was then found that in cases where the gap was of the order of 10 cm the post-operative stretching, how ever carefully carried out, generally damaged the nerve to such an extent as to preclude recovery (Highet and Holmes, 1943 Highet and Sanders, 1943)

In an analysis of 699 cases requiring operative repair Seddon (1947b) found that suture was possible in 499 (71 per cent) that an extraordinary form of repair was required in 65 (9 4 per cent) and that in 135 (19 5 per cent) nothing could be done because the extent of the lesion was too great. The cases treated by suture included a number in which the gap was considerable and in which no recovery had occurred He pointed out that the proportion in which suture was desirable—not merely technically possible—was, therefore appreciably less than 70 per cent

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The ideal material would be a graft from another species or from another person and preferably one that could be stored. Unfortunately all exogenous grafts have proved unsatisfactory Heterogenous nerve grafting is useless Fresh and stored homografts although promising experimentally have been tried at two of the British centres (Seddon and Holmes 1944 Barnes, Bacsich Wyburn and Kerr 1946) and by Spurling, Lyons, Whitcomb and Woodhall (1945) in the American Army and have been found wanting Seddon and Holmes (1944) suggested that their failure was analogous to that of homogenous skin grafts which, as Gibson and Medawar (1943) showed was due to the development of an active immunity to the transplanted tissue

It is possible that a homogenous graft could be treated in such a way as to render it less liable to provoke an unfavourable reaction Russian surgeons, in particular Propper-Grashchenkov (1942), favour fixation with formalin—though it is difficult to understand why—but there are no reliable records of cases successfully treated with such grafts and five cases dealt with in this manner by Bristow at Botley s Park have shown no signs of recovery There are, likewise, no reports of the successful clinical application of Weiss s (1943a, 1943b Weiss and Taylor 1943) frozen-dried homografts and experimental work by F K. Sanders (p 150) has given discouraging results. No British workers have experience in the use of heterogenous and homogenous grafts prepared by the method of Schabadasch (1944) which involves removal of lipoids, and impregnation of the graft with a solution containing glucose and magnesium glycerophosphate. Grafts prepared in this way were employed in 17 clinical cases, but when his paper was written (April 1943) the period of post-operative observation was still short, and no further report has as yet been published. *Thus attention must remain focussed on a method which of necessity has only* a limited application—namely autogenous grafting.

The success of nerve autografts in experimental animals is no longer in doubt. The evidence has been presented in Chapter III (see also Sanders, 1942 and Gutmann and Sanders, 1942) Seddon, Young and Holmes (1942) and Barnes Bacsich and Wyburn (1945) have also shown histologically that good regeneration may occur through human autogenous grafts. Thus it appeared likely that success or failure would be determined mainly by technique during the war years Seddon (1947b) made a detailed study of the conditions requisite for success and this chapter is based largely on the published account of this work. The results in patients operated on at other centres are included in the tables and the results in Seddon s own cases have been brought up to date. It is now evident that if certain conditions are observed autogenous nerve grafting may be relied on to give results not inferior to those seen after well-executed suture

B TECHNICAL CONSIDERATIONS

(i) *Donor Nerve*

The most serious limitation in the clinical application of nerve autografting is that of obtaining sufficient peripheral nervous tissue to allow repair of a large gap in a nerve of considerable diameter The aim must always be to implant a graft, or collection of grafts having a total cross-sectional area at least equal to that of the distal stump of the damaged nerve. Failure to observe this is, in part, responsible for some of the poor results that have been reported. The exiguity of supply often leaves the surgeon with no choice of materials, he must take what is available however certain points are worth bearing in mind

If a *cutaneous nerve* is to be used it should not have entered its zone of distribution—for example the lateral cutaneous nerve of the thigh below the anterior superior iliac spine, or the small sciatic below the gluteal fold Nerves such as these give off branches throughout their course below the sites mentioned, with the result that their distal diameter is much smaller than their proximal There are four suitable cutaneous nerves the internal cutaneous of the forearm proximal to its bifurcation at the elbow the available length ranging from 20 to 27 cm the superficial radial nerve between the elbow and the wrist, yielding a length of 20 to 25 cm the sural (external saphenous)

between its origin and the lateral malleolus, yielding a length of 25 to 40 cm depending on the level of junction of its two nerves of origin and the (internal) saphenous in the thigh—up to 40 cm All four nerves have much the same diameter about 2 to 3 mm

Before using the sural nerve it was formerly customary to carry out a block with a local anaesthetic in order to determine whether the resulting zone of insensibility extended on to the heel In no case was there any such extension and therefore there is probably no risk of trophic ulceration following resection of the sural nerve The superficial radial nerve should not be used for repair of the median unless the radial itself is irreparably damaged If the superficial radial nerve is excised on the injured side then the patient is deprived of such benefits as would result from sensory overlapping from the superficial radial into the median area. If the contralateral superficial radial nerve is used the patient will then have two sub-normal hands instead of one.

There is a possible theoretical objection to the use of cutaneous nerves for the repair of nerves containing motor fibres (Gutmann and Sanders 1943) As nerve-fibres subserving motor and proprioceptive functions are the largest and the fibres in cutaneous nerves are never of a size equal to them it is possible that motor recovery through a cutaneous nerve graft would be appreciably inferior to recovery of cutaneous sensibility The available clinical evidence shows that this possible objection does not hold and Simpson and Young (1945) have shown that large fibres from the central stump have no difficulty in dilating rather small peripheral tubes, and so attaining a diameter sufficient for effective function.

Other small nerves have been used in exceptional cases, the reasons for employing them being their ready availability or the fact that they also had been severed and could not be repaired

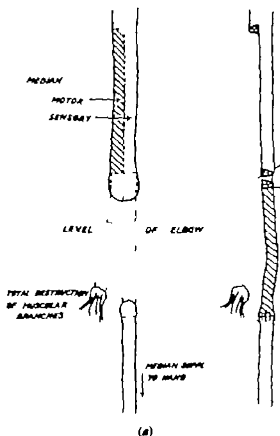
A *segment of a trunk of a main nerve* may be used where two main nerves have been so extensively damaged that neither can be repaired by suture or where the function of one nerve is so predominantly important that it is justifiable to take a graft from the other for its repair even though suture of the less important nerve is possible. Since it is now evident that main trunk grafting of the median nerve is a fairly reliable procedure, it might even be justifiable to take a segment from an intact radial nerve for repair of a gap in the median

TABLE 109

Sources of material used for grafting

Cutaneous nerves	
Medial cutaneous of forearm	24
Sural	10
Superficial radial	7
Others	5
Main trunk	
Ulnar	10
Lateral popliteal	8
Half-thickness median	3
Radial	2
Others	4

too large to be closed by a cable of cutaneous nerve grafts As will be seen from Table 109 the ulnar nerve has been used most frequently as a graft the radial, the lateral popliteal and even the whole sciatic have also been employed, and in three cases (Fig. 265) the median nerve itself has been split in order to provide a graft for repair of the other half of the nerve, in which there was some prospect of restoring function. This technique is hardly admissible except where the graft is taken from the nerve, as it was in these three



(a)



(b)

FIG 265 (a) Diagram of operation in which one half of the trunk of the median nerve was used for repair of the other (b) The graft in situ (E.12, Table 112).

cases just proximal to the main bifurcation and distal to the main intraneural plexus that is to be found a few centimetres above every set of branches In effect one *branch* of a nerve is used for repair of the other

An objection to the use of main trunk grafts is the risk of a greater or lesser degree of necrosis It has been reported (Sanders 1942) and was observed in one of our cases by Holmes (1947a) Yet histological observations made by Barnes *et al* (1945) and Holmes (1947a) show that a large graft may survive There may well be a critical diameter which it is unwise to exceed and it is possible that the size of the lateral popliteal nerve the largest that has been employed apart from one main sciatic nerve graft exceeds the limit of safety There was undoubted evidence of ischaemic change in one lateral popliteal nerve graft (Holmes, 1947a) and the clinical results have hardly been encouraging (Table 113) The ingenious nerve-pedicle grafting operation described by Strange (1947 1950) and used with success as early as March 1945 by the Winwick workers, should be employed where grafts of large diameter are necessary (Fig 267) However the clinical evidence of recovery after main trunk nerve grafts in the upper limb indicates that the degree of ischaemia in the graft cannot be serious.

The possible merits of *predegenerate grafts* have frequently been debated and there are two reasons why they might be superior The degenerated axons and myelin having been absorbed there are then free channels waiting to receive the outgrowing axons there is also a great increase in the number and activity of the Schwann cells—greatest, according to Abercrombie and Johnson (1942) between the nineteenth and twenty fifth days—which should ensure better unions with the host nerve. Yet Bunnell and Boyes (1939) and Sanders and Young (1942) found no significant difference in regeneration through fresh grafts compared with that seen after implantation of predegenerate ones. There is much to be said against the latter procedure. It is true that when the extent of the gap to be repaired is known the small preliminary operation of severance of the donor nerve could be carried out a few weeks before the final procedure. But unfortunately the exact state of affairs is rarely known until the definitive operation and after the stumps of the damaged nerve have been exposed and the extent of the damage has been determined it would hardly be justifiable to close the wound then proceed to divide the donor nerve, and three or four weeks later perform a second major operation The lateral popliteal graft may be a special case. The one example of necrosis, mentioned above, occurred in a graft taken from the central segment of the lateral popliteal nerve (Holmes, 1947a) whereas the graft taken from the distal segment of the same nerve seven months after injury showed no necrosis and contained regenerating fibres of large size (see p 153)

In a number of cases it was necessary to use the distal and therefore degenerated segment of a divided nerve as a graft. Degeneration dated from the original injury and was often of many months standing. The final results in these cases were not altogether encouraging, and it is possible that longstanding degeneration of a graft was positively harmful because the considerable shrinkage of the Schwann tubes (Holmes and Young, 1942 Sanders and Young, 1944) prevented the outgrowing nerve fibres from attaining diameters adequate for satisfactory function In the case described by Barnes *et al* (1945) the graft taken from the distal segment of the ulnar nerve 613 days after injury was found to contain only very small fibres

In one case of digital nerve injury (Table 110) two of the grafts were fresh and two had been degenerate for nine months satisfactory regeneration occurred through the former but not through the latter As there was no excess of collagen in the stumps of the recipient nerves it was possible that this failure was due to the state of the grafts. Yet in this and other similar cases the shrinkage

TABLE 110

Digital nerve-grafts

No	Interval (months)		Extent of gaps (cm.)						State of distal stumps		Result
				Cutaneous					Collagen		
	before healing	between injury and repair	Motor	1	2	3	4	5	Peri-fascicular	Intra-fascicular	
Mc.I	4	35	—	—	—	—	6	—	+++	+++	Failure
C.19	10	11	—	3 5	5 7	5·1	5·5	—	++++	++++	Failure
A 12	¾	8	—	—	—	—	4 5	—	+++	+++	Failure
S.27	1	9	2 5	4	5 5	—	—	—	N	N	Failure
F 11	½	13	—	2 8	1 5	—	—	—	++	N	Success
N 13	1½	9	—	3 5	4	—	5 5	4 8	1, 2} + 4, 5} +++	+ +++	Success in 1 and 2 Failure in 4 and 5
S.93	7	10	—	6	7	10	8	—	N	N	Success
Mc.20A	¾	8	—	3 5	3 5	4	—	—	1, 2} +++ 3 N	+++ ++	Success
L.49	1½	11	—	—	—	4 7	0 7	—	+	+	Success
M 96	½	7	—	3 5	3 7	3 5	5	—	+++	+++	Partial recovery
G.63	1	3	—	3	3	2 8	2 5	2 7	N	N	Success
R.63	½	6	—	5	5	5	—	—	N	N	Success
K.30	¾	10	—	4 5	5	7	4 8	—	+	+	Failure
C 134	2	3	—	—	1 2	2 2	—	—	N	N	Success
H 150	½	14	—	—	—	2 8	2 4	1·6	N	N	Failure
S.175	1½	5	—	—	—	—	3	4 2	N	N	Partial recovery

of Schwann tubes in the donor nerve cannot have exceeded that in the distal segment of the recipient nerve unless temporary devascularization of the graft after its resection greatly aggravates the shrinkage, the failure cannot be ascribed with certainty to the state of the graft

(ii) *Operative Procedure*

The technique of autogenous nerve grafting is similar to that for secondary suture, and description will be limited to points of particular importance.

(*a*) *Cutaneous scarring* Since wounds of nerves that call for repair by grafting are usually extensive the need often arises for replacement of the scarred skin by healthy tissue. Nothing less than a full thickness flap or tube pedicle graft will suffice since it is important that the nerve graft should lie, as far as possible, in healthy well vascularized tissue There are occasionally circumstances in which it is justifiable to leave the scar untouched and this will be referred to later When the first operation for plastic repair of the skin is undertaken the stumps of the divided nerve should be exposed. This will enable the surgeon to determine the extent of the gap and whether the nerve can be repaired by secondary suture or by grafting. The plastic repair if indicated should be carried to a conclusion as rapidly as possible so as not to add unduly to the delay between the original injury and the final repair of the nerve. On the other hand if the gap is too great to be closed then there is probably no point in proceeding with an elaborate plastic skin repair replacement of the scar by a split-skin graft may suffice.

(*b*) *Exposure of nerve mobilization of stumps* The technique is that required for secondary suture except that there will be no need to prolong the incision for mobilization of the stumps unless the gap is so long that with the supply of graft material at the surgeon s disposal it cannot be closed by grafting alone. He must then consider whether reduction of the gap by full mobilization of the segments will make grafting possible. If there is a reasonable prospect of success, full mobilization of the segments should be carried out and after they have been approximated as much as possible, the neighbouring joint being flexed to a convenient degree, the remaining gap should be bridged by a graft.

(*c*) *Suture possible but undesirable* Here it is convenient to consider the case in which suture is anatomically possible but undesirable on account of the degree of flexion necessary to bring the ends together after trimming It has been shown that when a nerve has been sutured with a joint or joints in extreme flexion it may be damaged by the stretching required to straighten the limb As a practical guide it may be said that more than 90 flexion of the knee or the elbow is undesirable The best procedure is to flex the joint between 70° and 90° then to approximate the ends as much as possible, and to bridge the remaining gap by a graft.

(*d*) *Resection of end-bulbs* There is rarely any risk of inadequate resection of the proximal stump since the very existence of a neuroma is an indication that it contains healthy axons. Resection at the upper limit of the neuroma generally ensures the exposure of bundles that have not been affected by retrograde degeneration Even when the neuroma is buried in scar there is no difficulty because on cutting across the nerve the translucent mobile bundles in a healthy proximal segment are clearly recognizable. Unfortunately the distal stump cannot be approached with the same certainty since (pp 112, 118) there may be a heavy deposit of collagen within the bundles of the distal segment (Holmes

1947a), which often cannot be recognized by the naked eye Therefore the distal resection should be generous, especially in digital nerves This recommendation is of course based on the assumption that the collagenization is of limited extent (see Holmes, 1947a)

(*e*) *Bed for graft* Though a graft is vascularized chiefly from the nerve stumps the risk of ischaemia should not be increased by allowing it to lie in a badly scarred bed Every attempt must be made to excise scar tissue, and if the difficulties in doing this are insuperable the graft may sometimes be threaded beneath the scar through a tunnel of healthy tissue, or as in the following procedure.

(*f*) *By pass operation* This simple procedure may sometimes be employed with great advantage it is best understood by description of a particular instance.

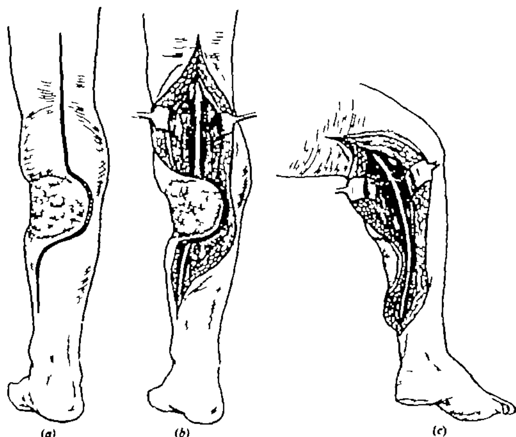


FIG 266. The by-pass operation. (*a*) Skin incision carried to one side of the deep scar through healthy tissue (*b*) Central and peripheral stumps isolated above and below the scar (*c*) After mobilization of the central stump and flexion of the knee the nerve-ends were laid in the by-pass and united with three strands of cutaneous nerve. Plasma-clot fixation (B.146a, Table 111).

In a case of posterior tibial nerve injury (Fig. 266) it was known that all the structures in the calf had been divided by an enormous pressure sore. This deep scar was therefore, left undisturbed while the stumps of the nerve were isolated above and below No attempt was made to perform a clean dissection of the end bulbs which were severed at the points where they entered the dense scar The incisions above and below the scar were then joined by one passing well to the side of it, through healthy subcutaneous tissue and deep fascia After resection of the stumps it was found that the gap was greater than

could be closed by grafting alone, and the proximal stump was therefore mobilized to the upper end of the popliteal fossa With the knee flexed 90 the proximal stump was then drawn down into the by pass and anchored there. The remaining gap of 5 cm was easily closed with a cable of three strands taken from the lateral root of the sural nerve

(g) *Pedicle-graft operation* This is illustrated in Fig. 267 It is indicated when a large nerve has to be used as a graft, the lateral popliteal for example, though it has been employed only in the upper limb where free main-trunk grafts have been used with success The other indication for its employment is where the graft must of necessity traverse a densely scarred bed and it is the ideal operation in the rare case where ischaemia of the forearm has damaged the median and ulnar nerves beyond hope of recovery and the latter is used for repair of the more important nerve (see Table 115 J L)

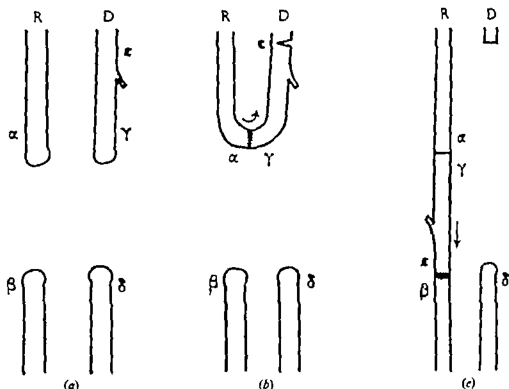
(h) *Preparation of graft* After the extent of the gap to be closed has been accurately determined a graft of appropriate length is prepared As it is well recognized (Sanders and Young, 1942) that grafts shrink, it is wise to prepare a graft about 15 per cent longer than the gap to be closed Whether a cutaneous nerve graft, single or in the form of a cable, or a main-trunk is employed depends upon the particular circumstances. If other material is obtainable a graft should not be taken from the distal segment of a divided nerve when the injury has occurred more than six months previously

(i) *Suture of graft use of plasma clot* A number of ingenious methods of suture of cable grafts have been described they are all intricate and it must be conceded that a cutaneous nerve, on account of its loose structure and the thinness and mobility of its sheath is hardly suitable material for precise suture with thread Accurate fixation of small grafts has been greatly facilitated by the introduction of plasma suture (Young and Medawar 1940 Seddon and Medawar 1942) The procedure is as follows the field of operation must be dry fibrin foam may be employed to control oozing, especially from the cut surfaces of the central and peripheral stumps The grafts are laid in position and their ends accurately opposed to the stumps provided that the grafts have not been moistened with saline it will be found that they are sufficiently 'tacky' to adhere slightly to the cut surfaces of the nerve The operating table is so manipulated as to make the bed of the graft a horizontal hollow Bone wax or fibrin foam may be used temporarily to build up any gaps in the sides of the lake, so that it will form a convenient receptacle for the plasma. It has not been found convenient to use the plasma suture moulds devised by Tarlov (1944) An assistant then drops the prepared plasma* from a fine pipette on

* It is now possible to obtain dried fibrinogen and thrombin from the Lister Institute and the instructions issued for their use are as follows

After removal of the stopper from the bottle containing the fibrinogen, *sterile distilled* water is added up to the 10 ml. mark. The fibrinogen is dissolved by gentle rotation, shaking of the bottle being avoided. All but a few flakes will dissolve in ten minutes, and the whole of the fibrinogen will be in solution in the course of an hour The resulting faintly opalescent solution may be kept for many weeks in the refrigerator The other bottle contains 50 units of thrombin to which 1 5 to 2 0 ml. of saline are added. An opalescent suspension is formed in a minute or two and it must not be used after being stored for more than a week.

Two drops of the thrombin solution are placed in each of three or four mixing tubes. For each application about 1 ml. of the fibrinogen solution (about twenty drops) is added and mixed thoroughly with the thrombin. The mixture is dripped on to the site of application with a fine pipette within a few seconds of mixing, and it rapidly sets to form a firm clot A fresh pipette must be used for each application.



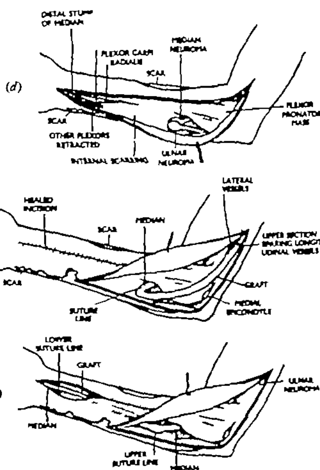


FIG. 267 The nerve pedicle described by F G St. C Strange, applicable to cases where adjoining main nerve trunks have been damaged over a considerable length.

(a) Shows the site of the nerve stumps. R = recipient nerve. D = donor nerve.

(b) The first anastomosis, with proximal division of the nerve bundles but not of the longitudinal vessels in the donor nerve.

(c) The anastomosis completed.

(d), (e), (f) The application of this operation for repair of the median nerve.

to one junction the surgeon concentrating all his attention on the line of suture He may find it necessary to hold one or more grafts in position with watchmaker s forceps, which can be withdrawn without disturbance after the plasma has clotted A second batch of plasma is then prepared and applied to the distal suture line In order that the grafts may acquire part of their blood supply from the surrounding tissue, it is wise (Tarlov and Epstein 1945) to avoid application of plasma to the grafts throughout their length, though in practice this is often difficult

A main trunk graft may be stitched to the stumps in the ordinary way plasma has no particular advantages and if there is any tendency for the sheaths of the stumps or of the graft to evert it is distinctly inferior to stitches. Davis and Cleveland (1934) have recommended resection and resuture of the distal junction at about the time when the axons may be expected to have grown across the graft. They believe that invasion of the distal junction by fibrous tissue obstructs the passage of axons from the graft into the distal stump However since union at a suture line is brought about primarily by the outgrowth of Schwann cells, and since these grow more actively from the distal stump the distal junction ought if anything, to be more satisfactory than the proximal There is neither experimental nor clinical support for Davis and Cleveland s recommendation (Sanders and Young, 1942) It may be that separation of the distal suture line has sometimes occurred as a result of shrinkage of the graft, which may be obviated by the use of grafts longer than the gap to be closed All forms of wrapping, such as tantalum foil are to be avoided they interfere with vascularization of the graft

(j) *Repair of partially divided nerves* Partial suture of an incompletely divided nerve, the unaffected portion forming a lateral loop at the level of suture is not a satisfactory procedure. There is no epineurium on the intraneural aspect of the resected stumps, which means that stitches inserted on this aspect will almost inevitably damage nerve-bundles and some of the bundles, being unenclosed by epineurium will pout laterally An example of the repair of a partially divided nerve by inlaying an autogenous graft is illustrated in Fig. 268

C RESULTS

The methods employed in assessing results were the same as those in general use at all the centres (p 355) Since a detailed report on the results in 59 of the cases treated at the Oxford centre has been published elsewhere (Seddon 1947b) only a summary will be given here though with a sample of the detailed assessments (Table 112) to indicate how the terms *success* and *partial recovery* have been applied

With but few exceptions the cases presented lesions of great severity As will be seen from the tables the delay between injury and repair was often prolonged either on account of persistent infection or on account of the need for more or less elaborate plastic skin operations In the upper limb there was injury of a main blood vessel in a third of the patients In using the terms success and partial recovery it would be justifiable to compare the results obtained with those seen after end to-end suture of the same nerves under equally unfavourable conditions However a more rigid standard of com parison has been chosen for each case the best result observed after secondary suture of the same nerve for repair of a short gap at the same level as in the grafted case. This is an important point. It must be borne in mind that in

certain situations, for example, lesions of the ulnar nerve in the upper arm the results of the most carefully executed sutures, carried out under favourable conditions, are always imperfect.

Between January 1941 and October 1947 grafting was carried out in 67 cases at the Oxford Centre, in one at Edinburgh one at Killearn, and one at Botley's Park Four nerve pedicle operations were performed three at Winwick (where the operation originated though no account of it was published) and one at Oxford



(a)



(b)



(c)

FIG 268 Repair of a partial division of the ulnar nerve by inlay grafting. (a) The Lesion (b) Separation of damaged bundles, above, from normal bundles, below oozing from the nerve which would obscure this delicate dissection, is controlled by Crile clamps applied to the nerve above and below the lesion (c) Nerve repaired with one strand of the medial cutaneous nerve of the forearm, which was attached to the ulnar nerve with fine stitches. The length of the graft was left attached to its bed, so that part of its blood-supply was preserved. Result almost perfect restoration of function (J 49 Table 114) See p 399

(I) *Group A Digital Nerve Grafts* (see Table 110, p 394)

In two of the early cases, Mc.1 and A 12, the operations were experimental the patients disability being small but they were anxious that something should be attempted since the numbness was just sufficient to make them conscious of some loss of function There was an incised or lacerated wound in eleven cases and a gunshot wound in five. In none had there been prolonged sepsis or excessive scarring. In four cases the loss of skin was such as to require plastic repair by either a flap or a pedicle graft The average delay before nerve repair was considerable (ten months) and excellent recovery occurred in a case

where there was a thirteen month delay (F 11) The site and extent of the nerve gaps repaired are shown in Table 110 and Fig 269 The condition of the nerve

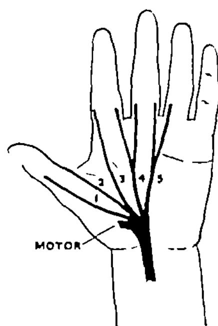


FIG 269 Diagram showing sites of nerve-grafting in the hand (see Table 110).

stumps, especially the distal proved to be a factor of prime importance in five cases in which there was extreme endoneurial collagenization no satis factory recovery occurred Such endoneurial scarring is commonly associated with damage to the digital vessels (p 118) It is reasonable to suppose that in those cases in which the distal stumps were satisfactory in spite of severance of the digital vessels, a satisfactory collateral circulation developed before irreversible ischaemic changes had occurred in the distal stumps Thus the chief reason for failure was collagenization of the distal stump There were also two cases S 27 and K.30 in which no recovery occurred although the state of the distal stumps was satisfactory something must have gone wrong at one or other of the suture lines or for some other reason the grafts failed to act as satisfactory channels for the outgrowing axons.

(ii) *Group B Cable Grafts* (see Table 111 p 404)

The four brachial plexus lesions were all due to traction in the first three the resection was inadequate and in A 17 extreme muscle wasting (demon strated histologically) was an additional cause of failure the interval between injury and repair being 21 months

The causes of the median nerve lesions were gunshot wounds (4) laceration (1) compound fracture (1) and a deep burn (1) In this last case (R.75) an extensive plastic repair was necessary and there was unfortunately such pro-found ischaemic collagenization of the distal stump as to preclude recovery

Grafting of the radial nerve was rarely required since the reconstructive treatment for radial paralysis tendon transplantation was generally so satis-factory In the three cases in which grafting operations were performed the circumstances were exceptional

(iii) *Group C Main-trunk Nerve Grafts* (see Tables 112 and 113 pps. 406 408)

In thirteen of the fifteen median nerve lesions the injury was due to a gunshot wound in one to traction (H 112, Fig. 270) and in one to a machine laceration of almost all the structures in the anterior compartment of the forearm.

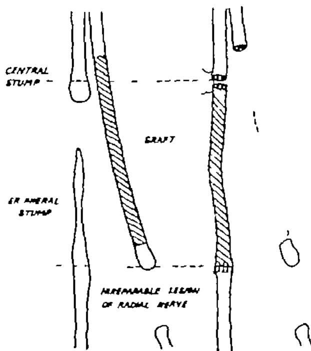


FIG 270 Extensive traction injury of median nerve and large gap in the radial due to an open wound. Graft from central stump of the radial used for repairing the gap in the median nerve (H 112, Table 112).

In nine of the fifteen cases of median nerve injury treated by main-trunk grafting there was division of the large blood-vessels In five loss of skin was such as to require plastic repair and in ten cases there was also an irreparable lesion of the ulnar nerve, which was the reason for the employment of this nerve as a graft for the median It is remarkable that such a high proportion of successes was obtained in view of the generally unfavourable nature of these injuries.

In eight cases of sciatic nerve injury strands of the lateral popliteal nerve were used as a graft for repair of the medial in four of them useful recovery has occurred. In another case of sciatic nerve injury with a large gap a main trunk sciatic graft taken from the other limb which had been amputated below the knee was used to bridge the gap

In H 58 the brachial plexus lesion was due to traction unfortunately resection was inadequate, though the procedure used probably has a place in the surgery of brachial plexus injuries. In a lesion of C 5 6 and 7 with complete paralysis of all muscles supplied by the radial nerve, the distal stump of the latter was used for the repair of C.5 the central stump of C 6 being so unsatisfactory as to preclude all possibility of successful repair

The last three cases in Group C differ from the rest in that the nerves involved were of comparatively small diameter The case of division of the

musculocutaneous nerve with a large gap was a striking success recovery in the biceps though not in brachialis, was little short of complete The attempt to repair the medial plantar nerve by using the proximal stump of the lateral plantar was an ill-conceived experiment. Subsequent experience has shown that the proper remedy in cases where limited mobilization is insufficient for end to-end suture of a low lesion of the posterior tibial nerve is mobilization of the nerve to the knee. This procedure is less formidable than it sounds and can be accomplished with little disturbance of the gastrocnemius or soleus muscles The attempt to repair a lesion of the deep branch of the ulnar nerve was unsuccessful on account of irreversible atrophy of the interossei

(iv) *Group D Inlay Grafts for the Repair of Partial Division* (see Table 114 p 409)

After repairing a partially divided nerve the assessment of recovery must be made with unusual caution recovery can only be relative, for the function mediated by the undamaged part of the nerve has to be compared with the sum total mediated by the nerve after repair of the damaged part by grafting. In the case illustrated in Fig. 268 (J 49 Table 114) the lesion was about 48 cm proximal to the wrist, and therefore no recovery in the hand occurring within less than about 500 days after operation could possibly have been due to the operative repair The operation was performed on August 9 1944 and the significant developments were those occurring after December 1945 There was a very striking improvement during 1946 With the exception of the first dorsal interosseous (3½) all the ulnar muscles worked at 4½/5 with excellent independent movement. The restoration of sensibility was equally gratifying, two-point discrimination on the pulp of the little finger being 8 mm. compared with 3 mm. on the normal side

Although this experience of repair of partial lesions by inlay grafting is limited, the collateral evidence provided by cases in which the whole thickness of a nerve has been repaired by grafting is so favourable that there should be no hesitation in using a procedure so technically unexceptionable. If a complete lesion can be repaired by grafting, then *a fortiori* a partial lesion may be dealt with in the same manner

(v) *Group E Nerve pedicle Grafts* (see Table 115 p 410)

This ingenious operation is designed to preserve the blood supply of a main trunk nerve graft in exactly the same way as in the transplantation of a large mass of skin. It has been used only in the upper limb but, in view of the good results obtained from free transplantation of a main trunk graft (Table 116) the need for so elaborate a procedure is not clamant. However if the graft must lie in an unsatisfactory bed the pedicle operation will ensure its survival in the last case in Table 115 the graft had to traverse a fibrotic and ischaemic forearm the damage being due to Volkmann's ischaemia. In all the other cases the median and ulnar nerves had been destroyed over a considerable extent by gunshot injuries. In the case with ischaemia these nerves had been reduced to fibrotic strands in the forearm

Either the proximal or distal segment of the donor nerve may be used depending largely on anatomical circumstances. About four to six weeks seems to be an appropriate interval between the two stages of the operation In the writer's case there was bleeding from the free end of the graft at the second operation an indication of satisfactory vascularization

TABLE 111

Group B cable grafts

No.	Nerve	Level	Interval (months) before healing	Interval (months) between injury and repair	Extent of gap (cm.)	Level of upper suture line (cm. bove or below elbow)	Donor nerve	Reason for grafting operation	Result
C 5	Cervical 5 6 (7)	Posterior triangle of neck	0	2	4	Transverse process	3 strands superficial radial. D.S.	End-to-end suture very difficult	Partial recovery
B 27	Cervical 5 6		0	6½	5·5		3 strands normal superficial radial		Failure
A 17	Cervical 5 (6)		0	21	5·8		3 strands normal superficial radial		Failure
B 216	Cervical (5) 6		0	3	3·2		3 strands normal medial cutaneous		Failure
Q 4	Cervical 5 6		0	9	4·6		9 strands saphenous and middle cutaneous of thigh		Recovery
W 82	Median	Forearm	9	13	12	10 below	3 strands normal sural	Precarious blood supply making mobilization undesirable	Success
Z 2	Median	Forearm	2	4	7·5	10·5 below	2 strands superficial radial from normal side and D.S. anterior interosseous injured side	Large gap	Success
H.133	Median	Forearm	9	18	3·4	16·5 below	3 strands P.S. superficial radial (irreparably damaged at wrist)	Large gap	Success
R.71	Median	Forearm	9	13	3·3	15·5 below	4 strands P.S. medial cutaneous	Large gap	Failure
R.164	Median	Forearm	4	8	6	20 below	2 strands P.S. medial cutaneous	Large gap	Partial recovery
R.78	Median	Axilla	2	2	4	32 above	2 strands normal medial cutaneous	Large gap	Success

BP 1446	Median	Mid-arm	1½	3½	9	—	2 strands P.S. medial cutaneous	Large gap	Partial recovery
S 107	Radial	Lower arm	5	6	10	4 above	2 strands D S. superficial radial	Joint stiffness precluded immediate tendon transplantation	Partial recovery
W 123	Radial	Upper arm	4	11	6	14 5 above	1 strand P.S. medial cutaneous	Uncertainty about power of muscles for transplantation	Partial recovery
S.131	Radial	Mid-arm	5	7	4·5	10 5 above	3 strands P.S. medial cutaneous	Patient opposed to tendon transplantation unless nerve completely irreparable	Success
R.146a	Posterior tibial	Mid-calf	4	10	5	7 above malleolus	3 strands of normal fibular communicating	Large gap	Success
M.125	Posterior tibial	Upper calf	0	27	9	21 above malleolus	3 strands P.S. sural	Large gap	Success

D.S. = Distal Stump P.S. = Pro imal Stump

TABLE 112

Group C main trunk grafts (median nerve)

No	Level	Interval (months)		Extent of gap (cm)	Level of upper suture line (cm above or below elbow)	Scarring	Donor nerve	Reason for grafting operation	Result
		before healing	between injury and repair						
L 12	Elbow	8	13	7	5 above	+	Half of P.S. median	Destruction of long flexors supplied by median nerve large gap limited movement at elbow	*Success* At 39 mth., A.P.B. 4 (other thenar muscles supplied by ulnar nerve) recovery of sensibility no over-reaction, localization fair two-point discrimination average 7 mm.
W 72	Elbow	1	11	6·5	2·5 above	None	Half of P.S. median	Failure of both sutures partial destruction of flexors supplied by median nerve	*Success* At 20 mth. F.P.L. 4-5 P.L. 4, F.D.P. 3 recovery of sensibility in all but distal halves of digits
L 79	Lower forearm	6	12	8	25 below	+ + +	Half of P.S. median	Mobilization inadvisable on account of scarring	*Success* At 24 mth. no recovery in thenar muscles, recovery of sensibility in thumb and index, two-point discrimination 3·8 cm.
S 63	Forearm	4	8	12	4 below	+	P.S. ulnar	Large gap in both nerves	*Success* At 24 mth. thenar muscles 4 at 28 mth. recovery of sensibility no over-reaction, localization poor two-point discrimination bad
M 66	Lower forearm	8	9	7	21 below	+ +	P.S. ulnar	Ulnar nerve hopelessly damaged mobilization of median undesirable on account of scarring	*Success* At 36 mth. thenars 3 recovery of sensibility no over reaction localization fairly good, two-point discrimination 15–20 mm.
C 113	Upper arm	9	10	8·2	21 above	+ +	P.S. ulnar	Large gaps; mobilization undesirable on account of scarring	*Recovering* At 22 mth. P.T. and F.C.R. 3, F.D.S. 2 some return of pain sensibility
B 206	Forearm	10	22	7	16 below	+ + +	P.S. ulnar	Late operation ulnar graft used, since suture of the ulnar lesion would have been valueless	*Partial recovery* No motor recovery anaesthesia of distal 2 phalanges of index and medius; slight over reaction

TABLE 113

Group C main-trunk grafts (various nerves)

No	Nerve	Interval (months) before healing	Interval (months) between injury and repair	Extent of gap (cm)	Level of upper suture line (in cm)	Scarring	Donor nerve*	Reason for grafting operation	Result
Ld 174	Medial popliteal	9	10	11	27 above knee	+++	1 strand lateral popliteal D.S.	Large gap	Failure
A 35	Medial popliteal	4	7	10	21 5 above knee	++	2 strands lateral popliteal, one proximal, one distal	Separation of suture	Partial recovery
W 80	Medial popliteal	11	16	12	41 above knee	++++	2 strands lateral popliteal, D.S.	Large gap, stiff knee	Failure
S 113	Medial popliteal	5	11	11 3	48 bove knee	+++	2 strands lateral popliteal, D.S.	Large gap	Failure
B 185	Sciatic	10	16	16	34 above knee	+	Main sciatic trunk from other side, below-knee amputation	Large gap	Failure
S 130	Medial popliteal	12	19	4 5	30 above knee	+++	1 strand lateral popliteal, P.S.	Large gap	Failure
B 193	Medial popliteal	1	9	5·5	14 5 above knee	0	2 strands lateral popliteal, P.S.	Large gap	Partial recovery
G 87	Medial popliteal	3	9	8 5	22 above knee	+	2 strands lateral popliteal, D S.	Large gap	Recoveri g
W 145	Medial popliteal	1	2	9	14 above knee	0	2 strands lateral popliteal, P.S.	Large gap	Partial recovery
H.58	Cervical 5 (6 7)	0	9	9 5	Transverse process of C 5	+	Radial, D.S.	Suture impossible	Failure
D 48	Musculo-cutaneous	2	5	7 5	3 5 below coracoid	+	1 strand normal medial cutaneous	Large gap	Success
J 33	Medial plantar	6	8	3	2 below malleolus	++	Lateral plantar P.S.	Alternative (probably better) would have been mobilization of posterior tibial nerve to knee	F ilure
W 73	Deep (motor) branch of ulnar	4½	6	4	Pisiform	++	Degenerate dorsal cutaneous branch of ulnar	Suture impossible	Failure

D S. = Distal stump. P.S. = Proximal stump

TABLE 114

Group D partial lesions inlay grafts

	Level	Interval (months)		Extent of gap (cm.)	Level of upper suture line (in cm.)	Scarring	Donor nerve	Result
		before healing	between injury and repair					
k of	Posterior triangle of neck	0	6	5·5	Transverse processes	0	3 strands of normal superficial radial	Success
um- f of	Lower arm	5	8	5	10 above elbow	0	1 strand of normal medial cutaneous	Success
of	Upper arm	1	1½	2·6	20 bove elbow	0	1 strand of normal medial cutaneous	Success
of	Upper arm	½	6	3	23·5 above elbow	0	1 strand of normal medial cutaneous	Recovering patient has gone abroad
con- ntly	Posterior triangle of neck	½	2	3 4·5 5	Transverse process	+	3 strands of normal medial cutaneous, each going to separate bundle below	Failure
of	Arm	2	5	1·5	6·5 above elbow	+	2 strands of normal medial cutaneous	Success

TABLE 115

Group E Nerve pedicle grafts

No.	Level	Interval (months)		Interval between first and final operations (weeks)	Extent of gap (cm.)	Source of graft*	Result
		before healing	between injury and first operation				
F G	Lower forearm	4	12	8	12 5	P.S.	Partial recovery
A. B	Forearm	12	13	6	10	D.S	Success
G B	Upper arm	? (P O W)	11	4	10	P.S	Success
J L.	Forearm	0	8	7	17	P.S.	Success

* P.S — Proximal stump D.S. — Distal stump

D DISCUSSION

In the period 1941–7 free autogenous nerve grafting was performed on 70 patients and nerve pedicle operations on four

Three cases of free grafting have been excluded from the analysis (Table 116), owing to defective post-operative data and the cases of nerve pedicle grafting are likewise excluded from this discussion In 28 cases (42 per cent) recovery was as good as that seen after the most satisfactory suture of the same nerve injured at the same level In a further five cases recovery is proceeding so satisfactorily that it is not unreasonable to anticipate that it will ultimately

TABLE 116

Summary of results

	Recovery	Recovering	Partial recovery	Failure	Total
A Digital	7	—	3	6	16
B Cable					
Median	4	—	2	1	7
Brachial plexus	—	1	1	3	5
Others	3	—	2	—	5
C Main trunk					
Median	9	2	2	2	15
Sciatic	—	1	3	5	9
Others	1	—	—	3	4
D Inlay for partial division	4	1	—	1	6
	28	5	13	21	67

good as in the first 28 thus the possible total of good results is 33-50 nt In a further thirteen cases there has been partial recovery which gh disappointing, is not altogether valueless hence the operation has l a useful return in no less than 46 out of 67 cases—68 per cent When it :mbered that most of the cases in which nerve grafting was performed had d exceptionally severe injury this record of success is impressive It shes autogenous grafting as a worthwhile and reliable procedure in eral nerve surgery It is now necessary to determine the factors essential to s

:rve grafting is compared with the grafting of two other kinds of tissue ind skin now both commonplace procedures, the most striking difference merges is that in the case of peripheral nerve tissue there is no margin hnical error In the grafting of skin or bone unfavourable factors such as apposition or moderate sepsis may mar the result though not necessarily :vably what has been lost may be only a small proportion of the whole e defect may be made good subsequently On the other hand the whole nism of nerve regeneration is one of such great delicacy that one single)urable factor or one technical mishap is enough to ruin a nerve graft d hope of redemption Success depends on the observance of the following , the first four of which are of equal importance in repair of a nerve ure

The interval between injury and repair should be as short as possible the moment of injury there is a progressively harmful shrinkage of the .nn tubes in the distal segment of the nerve an even more injurious ssive atrophy of denervated muscle, with interstitial fibrosis and disrance of motor end plates and similar though less well understood es in sensory end-organs and other tissues. Although there is a good :ct of repairing a nerve successfully at any time up to one year after there is little doubt that the sooner repair is carried out the better and sible steps should be taken to obtain early healing of wounds and fractures. A few cases have been seen in which sutured nerves came apart as a result sis. If a graft is used for repair of a nerve the possibility of its death l sepsis occur is an added hazard Operation should therefore, be post until sound healing of the original wound has occurred and protective)therapy is advisable. Sepsis was avoided in all cases reported here.

Resection of the nerve stumps must be adequate. There is no difficulty the proximal stump except in the case of a traction lesion where the nal damage is always considerable but, as has already been shown, there onsiderable risk of inadequate resection of the distal stump The distal ion should be generous, especially in digital nerves, in order to expose es that have not become collagenized as a result of ischaemia In every he state of the nerve stumps should be checked histologically

The preservation of a healthy condition of the joints muscles tendons, kin must be such that restoration of function will be satisfactory should iate regeneration follow repair of the nerve. Provided that it has not led nk ischaemia of the distal muscles damage to a main blood vessel seems ve surprisingly little harmful effect on the progress of recovery repair of ve either by suture or by grafting should not be withheld simply because has been division of say the axillary or brachial artery

ıer factors are peculiar to nerve grafting and naturally are chiefly con d with the graft itself

e The graft must be rather longer than the gap to be bridged so as to make allowance for shrinkage. If a graft of exactly the same length as the gap is employed, there is a risk of separation at one suture line. It has been suggested by Klar (1943) that a graft is not likely to be successful if its length exceeds 6 cm. this is not borne out by British experience. Cutaneous nerve-grafts (Tables 110 and 111), of 7 10 and even 12 cm have been employed with success a number of successes (Table 112) have also been recorded after the implantation of main trunk grafts of 8 12, and even 14 3 cm The results after bridging large gaps are as good as those in which only short grafts have been used

f The main-trunk graft or cable graft made up of strands of cutaneous nerve must have a cross-sectional area at least equal to the diameter of the distal stump otherwise there will not be a sufficient number of channels to ensure adequate re-innervation. Unfortunately the employment of a graft taken from a nerve trunk of considerable diameter introduces another risk of failure—necrosis or collagenization of the graft from ischaemia.

This is the reason for the poor results obtained after repair of the medial popliteal nerve with grafts taken from the lateral popliteal and in the one case where a segment of the whole sciatic nerve, from a limb that had been amputated through the thigh, was used to bridge a large gap in the sciatic nerve on the other side. It is possible that Strange s (1947) pedicle grafting technique will prove the solution to this problem.

g Such evidence as is available suggests that it is usually wiser to use normal nerve as a graft in preference to the distal stump of a divided nerve that has been degenerate for many months in cases where the latter has been used the results have been disappointing (p 393)

h The bed in which the graft lies is important in determining its survival, especially in the early days before satisfactory vascular connexions have been made with the proximal and distal stumps. If possible all scar tissue should be removed if this cannot be done then the graft should be led through a tunnel of healthy tissue, by passing the zone of cicatrization. For the same reason all wrapping materials should be avoided, and if plasma is used for fixation of the grafts it should be applied only at the junctions and not throughout their length. Haemostasis should be complete so that the graft will not be separated from its bed by an effusion of blood

i Suture. The effort expended in dissecting out the stumps of a badly damaged nerve and preparing them for repair is thrown away if the last and crucial step in the operation whether it be suture or the implantation of a graft, is not technically perfect. Yet sometimes the surgeon, after a long and exacting dissection perhaps not free from anxiety if he has been working in the neighbourhood of large blood vessels, comes to this final step with his vision a little dimmed and his hands no longer completely steady Unless he is still feeling fresh and confident of his dexterity it is best for him even at the risk of being considered fussy to leave the theatre for a few minutes and relax before completing the operation or he may ask a colleague, if one happens to be available, to perform the suture. Delicacy of touch often deteriorates after two or three hours continuous operating, and in these particular operations is at its lowest ebb at the time when it is needed most Fortunately where cutaneous nerve grafts are used—and they were formerly the most difficult of all to handle—suture has been greatly simplified by the introduction of concentrated plasma, though considerable skill is still necessary in maintaining

precise apposition of the grafts with the nerve stump before and during the application of the fibrinogen solution But at all costs the suture must be as nearly perfect as possible

The causes of failure (Table 117) are instructive and emphasize the importance of the several factors that have just been discussed In some cases more than one factor might have been responsible for failure.

TABLE 117

Causes of failure

Case		Undue delay (extreme muscle atrophy)	Inadequate resection (traction lesion)	Ischaemia of distal stump	Pre degenerate graft	Great scarring of bed for graft	Ischaemia of graft	No known reason
	Mc.1			+				
Table	C.19			+				
110	A 12			+				
Digital	S.27							+
nerve	N 13				+			
grafts	(part only)							
	M 96			+				
	K.30							+
Table	B.27		+					
111	A.17	+	? +					
Cable	R.75			+				
grafts	B 146a			+				
	B.206	+						
	D.59					+		
Tables	A.35						+	
112 and	W.80	+			+	+	+	
113	S 113				+	+	+	
Main-	B.198						+	
trunk	H.58				+			
grafts	J.33							+
	W 73	? +						
		3–4	1–2	6	4	3	4	3

2. Other Methods for the Closure of Large Gaps

Two other methods for the closure of large gaps require consideration They have been used over a long period and have enjoyed a reputation considerably more secure than that of nerve grafting. The operations of *bone shortening* and *bulb suture* are so well-known that there is no need to describe them. Yet authoritative information about the results obtained from these operations is scanty and for this reason the data given below although meagre are unusually valuable. Consideration of them will help to decide whether bone shortening and bulb suture are of use and, if so whether their place in peripheral nerve surgery has been taken to any extent, by nerve grafting, which is a technically simpler operation

(i) *Bulb Suture*

The results of 14 operations were observed at the five centres (Table 118) two of the operations details of which were incomplete, were performed before the patients came to a centre. The periods of post-operative observation ranged from 2½ to 5 years.

TABLE 118

Bulb suture

Centre	Case no.	Nerve	Total gap (cm.)	Result	Comments
Oxford	N 7	Median	8	M4½ S3 Success	
Warwick	J.H.	"	8.5	M0 S1 Failure	
Botley's Park	799		9·5	M2+S2+Success	
Botley's Park	1072	"	11.5	M3 S2 Success	
Oxford	K.19	"	11.7	M0 S2 Failure	Adolescent girl gap relatively greater than in an adult. Partial separation of suture line
Oxford	W 72		13.5	M1 S3 Success	Plus autogenous graft at second stage, 6.5 cm long
Oxford	M.8	Radial	6	M4 S2 Success	Limitation of movement of elbow prevented performance of ordinary secondary suture
Oxford	S 131		13	M4 — Success	Anterior transposition performed at first stage, which reduced gap by 2.5 cm.
Oxford	N.9	"	Not known	M0 S0 Failure	Operation elsewhere
Oxford	C.78	Ulnar	8.4	M3 S3 Success	Anterior transposition performed at first stage, which reduced gap by about 3 cm.
Oxford	L.77		Not known	M2 S1+Success	Operation elsewhere
Botley's Park	690	Sciatic	17.5	M0 S0 Failure	
Oxford	H.13	Lateral popliteal	14.8	M0 S1 Failure	Gaps probably too great
Edinburgh	300	Posterior tibial	14.7	M0 S0 Failure	

In two cases (not included in the Table) the first stage was performed but at the second operation it was found impossible to obtain apposition of healthy surfaces in the proximal and distal stumps, owing to the great extent of intraneural fibrosis In one case it was certain and in the other likely that the stretching after bulb suture had been too rapid and that a traction injury had been inflicted on the stumps. There is no objection to stretching being started immediately after bulb suture, but it must be controlled by means of a turnbuckle incorporated in the plaster and the rate of extension of the elbow or knee should not exceed 3° a day Thus a joint that is flexed 90° should be straightened in about one month

By this means it has been possible to perform suture when the gap produced by the injury and by the necessary resection of the end bulbs is as much as 11 cm. but not more. The patients were adults of average stature. Unless a second nerve in the limb has been damaged beyond hope of repair and can therefore be used as a main nerve trunk graft there is no other equally satisfactory means of closing a gap of that order it is therefore clear that bulb suture still has a definite place in the surgery of repair of large gaps. Furthermore by combining anterior transposition of the radial (Case S 131) or the ulnar (Case C 78) nerve with bulb suture, success can be achieved when either method alone would be inadequate Likewise, bulb suture may bring autogenous grafting within the range of possibility (Case W 72) Lastly bulb suture may be valuable where limitation of movement of a joint is such as to preclude

TABLE 119 (*continued*)

Bone shortening

Centre	Case	Nerve	Total gap (cm.)	Bone shortening* (cm.)	Result	Comments
			United Fractures—continued			
Botley's Park	951	Radial	11·0	5·0	M1 Failure	Plus anterior transposition
Winwick	W.H	Radial	12·0	5·0	M2. Partial recovery	
Oxford	N 17	Median	12·0	5·0 Radius and ulna	M2½S3 Success	
			No Fracture			
Winwick	W.J B	Radial	7·0	5·0	No follow-up	Went abroad
Winwick	F.R.	Radial	8·5	5·5	M0 Failure	Resection of distal stump inadequate
Killearn	J T	{Median Ulnar	6·0 9·0	5·5 Radius and ulna	M3+ S3+ in both. Success	
Winwick	E.P	{Median Ulnar	11·0 9·0	7·5	M1+ S2+ in both. Partial recovery	Non-union of bone. Median suture gave way and had to be repeated. Second osteosynthesis successful
Oxford	A15	Lateral popliteal	20	7·0 (Femur)	Repair of nerve impossible	Other femur 7 cm. short as result of improperly treated but well-united fracture

* Humerus unless otherwise stated.

Established non-union (nine patients) If there is a large nerve gap the indication for bone shortening is unequivocal unless the amount of shortening required to permit end to-end suture would be such as to produce a grotesque limb but even shortening of an order that would be considered disfiguring would be permissible if it were the only possible means of repairing two or more main nerve trunks. However shortening by 9 cm (Case B.S) was hardly justifiable for repair of the radial nerve alone nor even in Case P.85 where there was division of the radial and ulnar nerves. In this second instance suture of the ulnar nerve could have been performed as soon as the humerus was showing signs of union and recovery in flexor carpi ulnaris might well

X

OPEN WOUNDS OF THE BRACHIAL PLEXUS

by D M Brooks

1 Introduction

The brachial plexus sustained direct damage in 170 of the cases of peripheral nerve injuries that passed through the five main centres. The proportion of the total about 6 per cent, corresponds with that recorded after the First World War (Lehrmann 1921 Oppenheim, 1923 Pollock, 1926 Pollock and Davis 1933) and at Oxford after the Second World War (Brooks, 1949) it excludes isolated proximal lesions of the median, radial and ulnar nerves and traction injuries of the plexus. The damage was seldom uniform and a mixture of neurapraxia, axonotmesis, neurotmesis and undamaged nerve fibres was common. In many cases paralysis was at first complete, but rapid recovery occurred in part of the plexus within a few weeks leaving a residual paralysis which was slow to disappear and from which recovery was often imperfect

The main purpose of this survey is to establish whether open wounds of the brachial plexus should be treated in the same manner as more distal lesions of peripheral nerves, namely early exploration and, where necessary repair (Seddon, 1949a b). There are four specific questions

(1) Can the appearances disclosed at operation be interpreted reliably?

(2) In what proportion of cases is a neurotmesis present?

(3) Do the rules that normally govern resection of lesions in continuity apply to the brachial plexus?

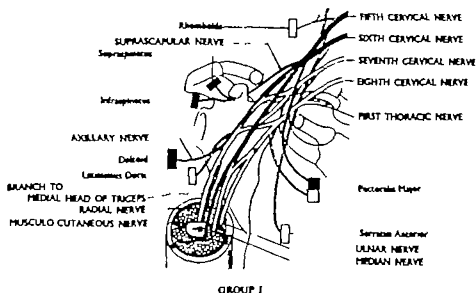
(4) *If repair is technically possible are the results such as to justify it?*

2 Material

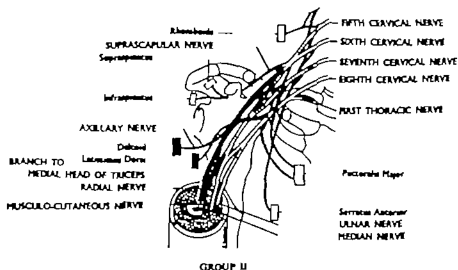
The 170 cases considered were those treated in the five main Peripheral Nerve Injuries Centres. *The survey includes the results of spontaneous recovery* reported at all the centres, but in considering operative exploration of the plexus, the findings at one centre only are analysed in detail since they are representative of the others.

Only those cases that were followed for at least two years are included in the tables of results consequently a proportion of the 170 had to be rejected because of inadequate periods of observation It is emphasized that only functionally significant recovery is under consideration

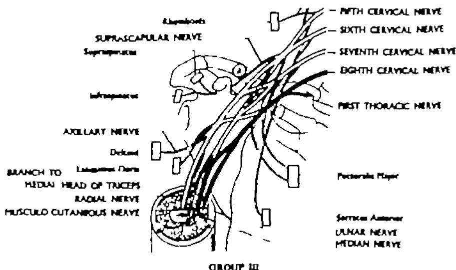
The upper trunk alone was most commonly involved and next in frequency were lesions affecting the whole of the plexus. This must have been due to the more exposed position of the upper trunk and the probability that lesions involving the lower trunks often proved fatal on account of damage to the underlying lung and adjacent great vessels.



GROUP I



GROUP II



GROUP III

FIG 271 Diagram illustrating the three groups of nerve lesions.

Table 120 shows the incidence of the various sites of injury

TABLE 120

Open wounds of brachial plexus showing incidence of part of plexus involved

Centre	No of cases	Group I*	Group II	Group III	Complete plexus	Groups I and II	Groups I and III	Groups II and III
Killearn	25	12	4	1	5	1	0	2
Gogapburn	43	14	4	5	7	3	2	8
Oxford	42	13	1	5	12	0	3	8
Botley s Park	38	12	3	4	10	1	3	5
Winwick	22	12	0	2	5	2	0	1
Total no	170	63	2	17	39	7	8	24
Per cent		38	7	8	25	5	5	14

* Group I = C5 + 6. Group II = posterior cord. Group III = C8 and T1 and medial cord

3 Method of Analysis and of Recording Results

There is no standard method of grading recovery in lesions of the brachial plexus, and in order to elaborate a satisfactory system, it was necessary to group cases according to the part of the plexus most involved The criteria applicable to a lesion of the upper trunk would be unsuitable for one affecting the medial cord for example motor recovery is all important after the former lesion and return of sensibility after the latter In order to compare cases a specific method of grouping (Fig 271) and grading of recovery has been adopted

Lesions of the roots and trunk of cervical 5 and 6	Group I
Lesions of the posterior cord	Group II
Lesions of cervical 8 and thoracic 1 and of the medial cord	Group III

In many cases the lesion involved more than one group thus after an injury involving the whole plexus, the grade of recovery must be expressed by a threefold statement.

Paralysis in Group I (the deltoid pectoralis major spinati biceps brachialis brachioradialis and extensor carpi radialis longus) results in loss of abduction and external rotation at the shoulder joint and loss of flexion at the elbow Recovery is expressed in terms of the ability to perform these movements muscle power being graded according to the system recommended by the Nerve Injuries Committee of the Medical Research Council Thus

Abduction	paralysis	A 0
	flicker of contraction	A 1

The power of external rotation at the shoulder and flexion at the elbow are similarly expressed, the figure being prefixed by E and F respectively. Sensory recovery after lesions of C5 and C6 is unimportant and is not discussed.

Lesions in Group II for the most part give rise to paralysis of the deltoid, teres major, latissimus dorsi, subscapularis, triceps and the forearm extensors. Recovery is expressed thus:

Triceps able to contract against gravity	P 1
Extensors of the wrist also able to contract against gravity	P 2
Extensors of the fingers also able to contract against gravity	P 3
Extensors of the thumb also able to contract against gravity	P 4
Full recovery	P 5

Here again sensory function, being unimportant, is left out of account.

In Group III recovery is expressed as that taking place in the distribution of the median and ulnar nerves. This method is anatomically inexact in that the proximal muscles supplied by the median nerve derive part of their innervation from the lateral cord. However, no significant errors could be traced to this compromise, and any attempt to refine the analysis would have made a difficult task impossible. The grading is based on that adopted by the Medical Research Council (p. 355).

Sensory recovery

- S 0 absence of sensibility in the autonomous zone of the nerve
- S 1 recovery of deep cutaneous pain sensibility within the autonomous zone
- S 1+ return of some degree of superficial pain sensibility
- S 2 return of superficial pain and tactile sensibility
- S 2+ return of superficial pain and tactile sensibility but with over reaction and inability to localize the stimulus
- S 3 return of pain and tactile sensibility without over reaction or with some ability to localize the stimulus
- S 3+ recovery as far as S 3 with good localization and some recovery of two-point discrimination
- S 4 complete recovery

Motor recovery

Median
- M 0 no contraction
- M 1 contraction in the proximal muscles but not against gravity
- M 1+ proximal muscles able to contract against gravity but paralysis of the thenar muscles
- M 2 proximal muscles able to contract against gravity and a flicker in the thenar muscles
- M 3 proximal and thenar muscles able to contract against resistance
- M 4 all muscles able to contract against strong resistance with some independent action
- M 5 full recovery in all muscles

Ulnar

- M 0 no contraction
- M 1 contraction in the proximal muscles but not against gravity
- M 1+ proximal muscles able to contract against gravity but paralysis of the intrinsic muscles of the hand
- M 2 proximal muscles able to contract against gravity some power in the hypothenars and little or none in the interossei
- M 2+ proximal and intrinsic muscles all active, but the first dorsal interosseous unable to contract against resistance
- M 3 proximal muscles hypothenars, and first dorsal interosseous able to contract against resistance
- M 4 as in Grade M.3 but with some independent lateral movement of fingers
- M.5 full recovery in all muscles

4 Results

Group I

The total of 117 cases comprised 63 in which the lesion was confined to the roots and trunk of C5 and C6 39 in which the whole plexus was involved, and fifteen in association with one of the other groups.

After eliminating those in which the period of observation was inadequate, 85 cases remained. Fig 272(A) shows that of these 85 cases which include degenerative and non-degenerative lesions, 76 regained flexion of the elbow 52 external rotation and 65 abduction all movements being performed against gravity and resistance. When the 46 degenerative lesions were considered alone it was found that recovery in them was almost as good (Fig. 272(B))

Fig. 273 illustrates the typical progress of recovery in thirteen upper trunk lesions from one centre. It will be seen that after two years little significant change took place. In assessing the prognosis it became clear that unless there was some evidence of motor recovery by nine months from the time of injury the outlook was sombre, though it happened that in the thirteen cases illustrated above all recovered abduction In over half the cases recovery in the biceps preceded that in the deltoid and the external rotators of the shoulder and on several occasions some action in the biceps persisted when motor paralysis was otherwise complete which suggests that the innervation of biceps may not always be limited to C.5 and 6 (Brooks, 1949)

Group II

There were only twelve cases in which the damage was confined to the posterior cord In the remaining 70 the posterior cord was damaged in association with other parts of the plexus, which is hardly surprising in view of its anatomical position The histogram (Fig. 274(A)) shows the number of cases that obtained a useful grade of recovery after two years and includes degenerative and non degenerative lesions Any recovery of less than Grade 3 (extensors of the fingers able to contract against gravity) is of little value and is therefore not shown

Fig. 274(B) shows the recovery in degenerative lesions only and it will be seen that about half the cases reached at least the lowest grade Fig. 275 (p 424) shows the typical progress of recovery in 21 cases from one centre little significant improvement occurred after two years. Where there was no evidence of recovery

(A)

(B)

Number of cases

Movements performed against gravity

Movements performed against gravity and resistance

A Abduction of shoulder

E External rotation of shoulder

F Flexion of elbow

FIG 272. Histogram showing (A) recovery at two years of 85 cases of degenerative and non-degenerative lesions of the upper trunk. (B) recovery at two years of degenerative lesions, 46 only

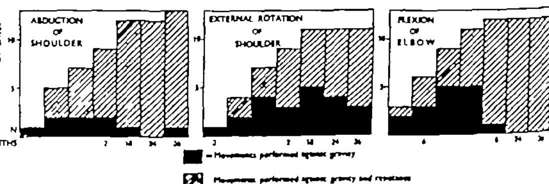


FIG 273 Histogram showing the progress of recovery in thirteen cases in which the lesion was limited to C5 and 6.

in triceps within nine months after the injury the prognosis was usually gloomy and was always so if there was no recovery within a year

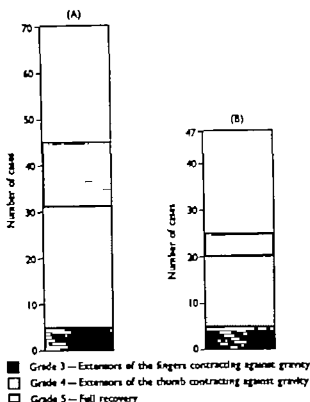


FIG. 274 Histogram showing (A) number of cases of injury to the posterior cord that showed a useful grade of recovery at two years, including both degenerative and non-degenerative lesions. (B) number of cases of injury to the posterior cord that obtained a useful grade of recovery at two years degenerative lesions only

Group III

The total of 88 patients in this group comprised 17 in which the lesion was confined to the medial cord, 39 in which there was injury of the whole plexus and a further 32 in which one of the other groups was also involved the progress of recovery was much the same throughout. When there was no evidence of motor recovery in the proximal muscles by one year the outlook was poor The motor recovery at two years in the 22 cases in which there was a complete degenerative lesion of the median nerve is shown in Fig. 276 In one of these cases the median paralysis occurred after the development of a traumatic aneurysm of the axillary artery and the lesion must have been due to compression at the end of two years recovery was M 3 S.3 This was the only case in which significant recovery took place in the distal muscles after a complete degenerative nerve lesion. In cases observed over a longer period there was no substantial improvement in motor function after the second year but in some the quality of sensibility continued to improve for up to four years from the time of injury as was observed by Pollock (1926) Sensory sparing carried no certain promise of adequate motor recovery

Recovery in the distribution of the ulnar nerve has not been presented separately since it ran parallel with that in the median distribution.

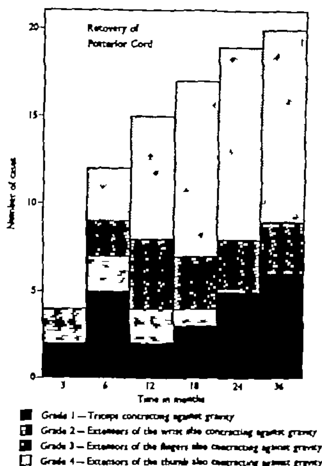


FIG. 275 Histogram showing the progress of recovery in 21 cases of injury of the posterior cord.

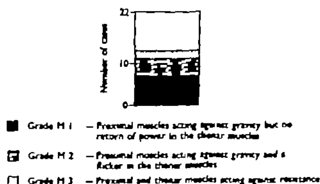


FIG 276 Histogram showing motor recovery in the median area at two years in the 22 cases in which there was a degenerative lesion of the medial cord.

Exploration of the Brachial Plexus

On 54 occasions, the brachial plexus was explored In general for one of three reasons firstly if there was a severe lesion involving the whole plexus secondly if there was a complete lesion of a part of the plexus and lastly for persistent pain in the limb An account follows of the types of lesions that were encountered in 22 explorations carried out at the Oxford Centre. More than one lesion and more than one type of lesion was sometimes found at exploration the total number of findings listed therefore exceeds 22.

Types of Lesions Encountered

1 No obvious change.
2. A degenerative appearance of the nerve
3 Nerve enveloped in scar with or without evidence of constriction
4 Neuromata (*a*) fusiform—firm or soft
(*b*) lateral.
5 Neurotmesis (interruption of continuity)

Intraneural scarring was never found except in association with a neuroma

Correlation of Operative Findings with Recovery Observed after Two Years from the Time of Injury

1 *No obvious change* In only four of the eight cases in which the part of plexus exposed showed no evidence of abnormality was the subsequent recovery at all good However in one it was likely that the lesion was distal to the field of exploration that is to say it was probably in the upper part of the axilla.

2. *Degenerative appearance of the nerve* In four cases part of the plexus was so described and indicated the greyish pink translucency characteristic of the peripheral part of a divided nerve, which is almost certainly due to the disappearance of myelin In two of these cases there was a proximal swelling of the nerve without any neuroma formation These lesions were described as axonotmesis and a favourable prognosis was given This forecast was subsequently justified in all cases so far as re-innervation of the proximal muscles was concerned but recovery in the distal muscles was uniformly poor

3 *Enveloping scar* Where there was extensive scarring round a part of the plexus, with no evidence of damage, recovery was good except in one case where a vascular lesion had caused peripheral ischaemic damage.

4 *Neuromata* (*a*) On two occasions a soft fusiform neuroma was seen and the subsequent recovery was good. In two cases where a firm neuroma was found one on the posterior cord and the other on the root of C7 recovery was very poor In one case, three soft neuromata were found, on the posterior and lateral cords and on the lateral root of median and fair recovery took place in each segment.

(*b*) In four cases a lateral neuroma was discovered. In two recovery was poor on the other hand recovery was good in the other two cases where the neuromata appeared to involve one third and two thirds of the nerve respectively

5 *Neurotmesis* In four cases complete loss of continuity was found and in three of them repair was possible. In one the upper trunk was divided two years after suture, flexion at the elbow against gravity and resistance was possible

divided. Repair by direct suture was impossible and the gaps were bridged by grafts from the medial cutaneous nerve of the forearm. There was no certain evidence of recovery three years later In the third case, the inner and outer heads of the median nerve were divided. The gap after resection was 6 cm. and suture was possible only after mobilization of the median nerve as far distally as the elbow with sacrifice of the branches to pronator teres. The grade of recovery at three years was M 1 S.2+ In the last case the lateral cord was divided together with the medial head of median. In the search for the distal stump of the median nerve it proved necessary to extend the dissection to 15 cm. below the coracoid process before it was found There was no obvious explanation for this wide gap unless the nerve trunk had been removed inadvertently at the time of the original wound excision.

5 Discussion

The most striking feature of these explorations (Table 121) was the infrequency of gross division of nerve tissue—16 instances in a series of 54 operations—

TABLE 121

Exploration of brachial plexus

Centre	No of cases	No of cases with division	No of cases repaired
Killearn	13	6	4
Gogarburn	11	5	3
Oxford	22	4	3
Botley's Park	3	1	1
Winwick	5	0	0
Total	54	16	11

whereas about half of the degenerative lesions due to more distally situated wounds showed more or less complete nerve division (Seddon 1948) It was also noteworthy that of these 16 cases where a division was found repair was possible in only 11 So-called neurolysis was an inevitable feature of these operations but there was no evidence that it was beneficial except perhaps in one case where it was followed by relief of persistent pain in the limb In most instances, scarring was severe and in consequence it was not always possible or safe to expose the entire plexus It was never deemed justifiable to resect a neuroma in continuity

It is clear that the gross findings are not a reliable guide to prognosis whereas in other situations the correlation is fairly accurate (Seddon, 1943 1949a and Chap II) Although electrical stimulation can give positive evidence of the integrity of nerve fibres in recent lesions a negative finding is valueless axonotmesis and severe intraneural scarring amounting to neurotmesis cannot be distinguished Trial section a valuable aid in more distal lesions is technically awkward on account of lack of mobility of the plexus and the consequent difficulty in inspecting a small transected area. Thus ancillary methods, which are often valuable in deciding for or against resection of the damaged segment are of little use in this region where they are really needed

TABLE 122

Results of repair of brachial plexus

Site of lesion	No of cases	Average delay before operation (months)	Useful recovery	Evidence recovery	No recovery
Upper trunk and branches	4	3	1	1	2
Middle trunk	1	2	—	1	—
Lower trunk	2	2	—	2	—
Lateral cord	2	3	—	1	1
Posterior cord	1	5	—	—	1
Medial cord	1	6	—	1	—
Total	11	3 (average)	1	6	4

Furthermore, the results of repair (Table 122) are not encouraging. The only worthwhile repair was of the upper trunk so perhaps better results might have been obtained in this group if as was usual in the treatment of open injuries of nerves elsewhere, exploration had been carried out in every case with complete paralysis of C5 and 6, and resection and suture performed not only where the trunk was divided but in cases where the nerve, although in continuity exhibited gross intraneural damage.

The conclusion reached from these exacting and time-consuming operations is that a reliable prognosis cannot be given except in those few cases where the nerve trunk is found to be divided or where a firm neuroma indicates that most of the thickness of the nerve is replaced by scar tissue.

In axonotmesis the conditions for recovery are the best possible the stroma of the nerve is largely preserved with the result that the outgrowing axons remain in their appropriate Schwann tubes The time factor is not important since in most nerves regeneration is complete before the harmful influence of delay becomes serious. In the upper trunk and in the posterior cord of the plexus the distance from the site of damage to the denervated muscles is relatively short but in the medial cord the distance to the muscles of the hand is much greater Recovery in Groups I and II was considerably better than in Group III it must be concluded that even after the most favourable type of degenerative lesion of the medial cord of the plexus, the distance to be traversed by the regenerating axons is so great that by the time they reach the periphery harmful involutionary changes are already well advanced in nerve muscle and probably skin. The harmful influence of delay on the recovery of motor function is due to the shrinkage of the empty Schwann tubes, atrophy of muscle fibres inter stitial fibrosis, and disappearance of motor end plates (Holmes and Young, 1942 Bowden and Gutmann 1944 Gutmann and Young, 1944 Gutmann 1948) It is possible though not clearly established that the effect on sensory regeneration may be similar It was shown however by Simpson and Young (1945) that the small size of Schwann tubes at the periphery may be less significant than was at first believed and it has been assumed increasingly that muscle atrophy is the more important factor Gutmann and Guttmann (1942b 1944) proved that in the rabbit regular intensive galvanic stimulation could be relied on to a remarkable degree to prevent atrophy of denervated

muscle and to maintain its normal state as determined histologically Useful return of power in the intrinsic muscles of the hand might therefore be expected after proximal nerve lesions in which there was a prospect of spontaneous recovery and in which recovery did in fact take place in the proximal muscles, provided only that wasting was retarded by regular galvanic stimulation. However the fact is that although such treatment is effective in lesions of the ulnar nerve (Jackson, 1945) recovery of functional significance in the small muscles of the hand after injuries of the brachial plexus rarely occurred This leads to the conclusion that shrinkage of Schwann tubes must be significant after all or that the beneficial effects of galvanic stimulation are of limited duration

It has been shown (Platt and Bristow 1924) that the nearer the lesion is to the cord, the more profound are the changes that occur in the anterior horn cells. It is just possible that in some instances these changes are significant and limit the extent of axonal regeneration, and therefore may account in some measure for the poor recovery in the distal muscles.

6 Summary

(1) One hundred and seventy open injuries of the brachial plexus were treated at five Peripheral Nerve Injuries Centres

(2) Methods of grouping and of grading recovery are described Group I—lesions of the roots and trunk of C5 and C6 Group II—lesions of the posterior cord Group III—lesions of the medial cord, C8 and T1

(3) Recovery in Group I was good in Group II fair and in Group III poor

(4) The plexus was explored on 54 occasions gross division of nerve tissue was found in sixteen cases and repair was carried out in eleven The single instance of useful recovery was after repair of the upper trunk and it is therefore concluded that with the possible exception of lesions of the upper trunk operative repair is valueless. Furthermore, the correlation of operative findings with subsequent recovery is so unreliable that exploration is of little value, even for the establishment of a prognosis.

(5) Recovery occurring after lesions in continuity was largely confined to the proximal muscles which suggests that regenerating axons cannot reach the hand before noxious changes in muscles and other structures have become irreversible this is a further indication of the futility of operative repair of lesions of the lower trunk.

(6) The good spontaneous recovery which occurred in Groups I and II the poor recovery in Group III even where there was apparently a favourable lesion in continuity the rarity with which division of nerve trunks was found and the discouraging results following repair make it necessary to conclude that exploration of open wounds of the brachial plexus is rarely profitable or justifiable.

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The line drawings in Chapter 7 are the work of Miss Diana Stanley Fig. 238 was drawn from a photograph kindly supplied by the Rehabilitation Department of Vauxhall Motors Ltd

Figs. 12 and 13 are from two water-colours which have hung for many years in the Department of Surgery University of Edinburgh They were painted by Mr J Souter of Aberdeen from patients injured in the first World War

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INDEX

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